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On September 30,1993, the Department of Physics at Hampton University was awarded a research instrumentation grant by the AFOSR for the development of an advanced Thermal and Electric Propulsion (TEP) system. Under this grant, a TEP test facility capable of providing 60-kW optical power for thermal propulsion and 30-kW electric power for the magnetoplasmadynamic (MPD) thruster has been constructed and installed. The TEP is literally of thermal and electric propulsion systems in a tandem order to take advantage of both systems. The TEP employs a high temperature thermal chamber for generation of an ionized propullant and a hollow cathode of the MPD as an expansion nozzle. Both feature alleviate the requirement of high voltage triggering and concentration of the current density on the solid cathode tip that commonly appear in the conventional MPD thrusters.

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Development of Advanced Thermal & Electric Propulsion (TEP) System.

FINAL REPORT

PRINCIPAL INVESTIGATOR

Bagher M. Tabibi

Nov. 25, 1994

AFOSR GRANT No. F49620-93-1-0611

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FINAL REPORT

DEVELOPMENT OF ADVANCED THERMAL & ELECTRIC PROPULSION (TEP) SYSTEM

SUMMARY

On September 30, 1993, the Department of Physics at Hampton University was awarded a research instrumentation grant (#F49620-93-1-0611) by the Air Force Office of Scientific Research, for the development of an advanced Thermal and Electric Propulsion (TEP) system. The amount of the grant was $431,650 for a period of one year endimg September 30, 1994. The purpose of the grant was to help Hampton University (a Historically Black University) to establish a research facility for the development of TEP system. Under this grant, a TEP test facility capable of providing 60-kW optical power for thermal propulsion and 30-kW electric power for the magnetoplasmadynamic (MPD) thruster has been constructed and installed.

The TEP is literally an integration of thermal and electric propulsion systems in a tandem order to take advantage of both systems. The TEP employs a high temperature thermal chamber for generation of an ionized propellant and a hollow cathode of the MPD as an expansion nozzle. Both features alleviate the requirement of high voltage triggering and concentration of the current density on the solid cathode tip that commonly appear in the conventional MPD thrusters.

The solar TEP or STEP system chosen for experiment is acquired in five packages; namely, a thermal and an MPD thruster nozzle with a test section, including a solar simulator (argon arc lamp), a vacuum pumping unit, a large vacuum tank, a thermal imaging system, and a data acquisition system. These subsystems have been procured, installed and tested on schedule. The complete system operation is now possible and diagnostics systems are now under installation.

To date, the formation of a research team is near completion with the PI, a faculty associate, a consultant, a postdoctoral research associate, 2-graduate students, and one undergraduate student. One more undergraduate student is being recruitment. The team is supported under a separate AFOSR Grant #F49620-94-1-0263 for operation and dianostics of the STEP system to establish proof of the STEP concept.

DEVELOPMENT OF ADVANCED THERMAL & ELECTRIC PROPULSION (TEP) SYSTEM

Introduction

The space propulsion system could be thermal, electric, and or chemical propulsion. Each of these propulsion systems is classified by its energy source. The thermal propulsion (TP) system, for example, uses energy sources which thermally energize the propellant medium. The TP system includes solar thermal propulsion (STP) [1], nuclear thermal propulsion (NTP) [2], arcjet, resistojet, and microwave-heated propulsion [3]. On the other hand, the electric propulsion (EP) system of which the propellant is energized by electrostatic or electromagnetic forces includes radio frequency electrostatic, field emission electrostatic, ion-jet, and (MPD) jet. Most of the advanced propulsion systems under study so far have either a high thrust with a low specific impulse I_{sp} <1000 sec (i.e. chemical and nuclear thermal) or a low thrust with a high I_{sp} (i.e ion amd MPD thrusters). Developing and positioning a propulsion system with the medium ranges of thrust and I_{sp} is more desirable and beneficial than those with such opposite extremes. A low thrust results in an unacceptably long trip time while a low I_{sp} accounts for high fuel and launch costs. The proposed concept of TEP is formulated by coupling thermal and electric propulsion thrusters in tandem [4]. Hence, the TEP system is featured with the advantages of both the thermal and electric propulsion systems and positions itself in the medium ranges of thrust and I_{sp} by overcoming the shortcomings of the separate propulsion concepts (see Reference [4] for detail). The schematic diagram of the STEP system is shown in Figure 1. A picture of the indoor part of the STEP system is presented in Figure 2.

The Department of Physics at Hampton University was awarded a grant (F49620-93-1-0611) for setting up a Solar TEP (STEP) for subsequent research under a separate grant.

The following sections report details of the STEP system which has been acquired and installed at the University.

Equipment's Acquisition

The equipment described in the Grant for the Solar Thermal and Electric Propulsion (STEP) system being developed at Hampton University has been divided into 5 packages for acquisition. Package I consisted of 8

major parts, (1) a thruster chamber, (2) a MPD thruster nozzle, (3) a MPD power supply, (4) a test section with 4 windows, (5) an isolation valve, (6) A thruster stand, (7) a solar simulator, and (8) an elliptical reflector. Package II is the vacuum pumping system. Package III is the vacuum tank which required fabrication and installation. Package IV is the thermal imaging system and package V is the data acquisition system.

Some other equipment for the TEP system such as mass flow controller, high and low pressure sensors, thermometers, air compressor, two stage pressure regulators, and a refrigerated cooling unit were purchased separately from those packages.

The requests for the price quotations of the packages were released to those potential vendors for bid through the university acquisition department in October 1993, and the contract awards were processed according to the qualification, price, and delivery requirement. The acquisition, fabrication, and installation were contracted with the following sources:

Packag I :	**STEP Thruster**	**Date**
Contractor:	Integra Tek, Inc. 11 Trotters Bridge Drive Poquoson, VA 23668 Tel: (804) 868-8949	12/13/93
Package II :	**Vacuum Pumping System**	
Contractor:	Kinney Vacuum Co 494 Turnpike Street, Canton, MA. 02021 Tel: (617) 828-9500	02/02/94
Package III:	**Vacuum Tank**	
Contractor:	Modern Welding Co. of Georgia Inc. P. O. Box 10067 Augusta, Georgia 30903 Tel: (404) 722-3411	12/21/93
Package IV:	**Thermal Imaging System**	
Manfacturer:	Inframetrics 16 Esquire Road N. Billerica, MA. 01862 Tel: (508) 670-5555	05/06/94

Package V: **Data Acquisition System**
Contractor: Nondeterministic System Corporation 09/31/94
107 Villa Rd
Newport News, VA. 23601
Tel: (804) 596-9466

The five packages, delivered at various times, are now installed on site in Room 100 of Armstrong-Slater Building, Hampton University campus.

The following sections summarize the detail of each part of the packages.

Package I

a. Thruster Chamber.

The thruster chamber was designed to provide stagnation temperature in excess of 3000 K using an optical power. Figure 3 shows the dimensional diagram of the thermal chamber. The requirements for the thermal chamber were: high melting temperature, high conductivity, endurance in thermal shock cycle, high strength and lower thermal expansion rate. These requirements are crucial for the adequate and long term operation of the STEP system. Some condidate materials are listed in Table1. Among them thungsten material was selected as the first choice. Even though HfC has the highest melting temperature, this refractory material is relatively weak for thermal shock.

The thermal chamber is housed in the focal line of an elliptical cylindrical reflector . The arc lamp with a 11 mm diameter is located at the other focal line of the elliptical reflector (see Fig. 4). The optical coupling efficiency of the elliptical reflector is more than 60%. The outside diameter of the thermal chamber is 14 mm which is close to the diameter of the arc (11 mm). Considering an overall coupling optical flux efficiency, a thermal flux of approximately 684 W/cm^2 can be obtained on the surface of thermal chamber. The diameter of the thermal chamber was restricted by the geometrical image of the arc and the elliptical reflector. The equilibrium temperature on the tungsten surface can be stated as:

(Optical energy absorbed = Radiation emitted + Convection loss to gas + Conduction through nozzle) .

$$\alpha_s \sigma T_s^4 = \varepsilon \sigma T_s^4 + h(T_s - T_a) + k\frac{dT}{d\tau} \qquad (1)$$

where, α = absorptivity of the body
σ = Stefan-Boltzmann constant
T_S = surface temperature
ε = emissivity of the body
h = heat transfer coefficient
T_a = ambient temperature
k = thermal conductivity.

If the convection and conduction losses are negligible, then equation (1) becomes as simple as:

$$T_s = \frac{(q)^{\frac{1}{4}}}{\alpha\sigma},$$

where q is the thermal flux on the tungsten surface. Substituting the numerical values, q = 6.84 x 10^6 W/m^2 and α = 0.51 [5], the maximum surface temperature could be reached approximaely 3,922 K with the thermal flux of 684 W/cm^2 on the surface. To consider the losses due to conduction and covection, we need to solve the equation (1) with approximate values. Using the existing information [5,6] the loss of the surface temperature will be 232 K due to mechanisms as described previously. Therefore, the surface temperature of the thermal chamber could be calculated as 3,690 K.

A thickness of the thermal chamber was determined not only on structure safety against the high pressures, but also on performance of heating which depends on the thermal time constant of material. The thickness of the chamber wall used is 2 mm. A picture of the thermal chamber with the MPD thruster nozzle is presented in Figure 5.

b. MPD Thruster Nozzle.

Figure 6 shows the MPD thrust nozzle diagram. The MPD nozzle enhances the specific impulse and provides an additional thrust. This nozzle consists of three anode electrodes paired with a hollow cathode. The anode electrodes are separated by insolators between and each of the anodes has a voltage differential. The MPD nozzle uses a low voltage (44 V) between cathode and anode of the MPD. Free electrons, generated in the thermal chamber by the solar thermal energy, initiate electrical

breakdown between electrodes of the MPD thruster. Unlike a conventional MPD thruster, no high voltage trigger is required to initiate the breakdown.

The MPD thruster nozzle is placed, and connected with ASA flanges between the thermal thruster chamber and the test chamber. The internal wall of the MPD nozzle is fine-machined after assembling all electrodes. Each anode has a water-cooling system to prevent excessive heating from the thermal and electric heating. For the first operation, the first anode electrode and the ground will be connected to the power supply. The optimum conditions for the operation will be determined by the tests using applied currents and voltages as well as the use of combination of the electrodes.

The full cone angle of the MPD nozzle is 50^{o} which will provide more axial component (thruster vector) of the **J** x **B** forces and prevent the surface discharge between the electrodes. A picture of the MPD thrust nozzle is shown in Figure 7.

c. MPD Power Supply.

Two Gold Star 600 Amperes/44 Volts DC power supplies with complete remote controller were purchased to provide electrical power for MPD thruster. The features and specifications for each power supply are as follow:

Specifications	Description
Output Control:	Adjusted over the full range using a remote control.
Type of Output:	Constant current/Direct current
Maximum Open Circuit Voltage:	70 Volts DC
Input Power:	3 phase; 230 Volts AC; 114 A; 60 Hz.
Rated Output	600 A, 44 VDC at 60% Duty Cycle
Amperage Range:	Low: 30-415A; High: 57-775A.

Figure 8 shows a picture of the DC power supplies.

d. Test Section.

Figure 9 presents a picture of the stainless steel test section. The test section has a configuration that allows the inlet and outlet of propellant and measurements of the nozzle velocity and density profile of nozzle-exit flow field by the laser Doppler velocimetry (LDV) and laser-induced fluorescence (LIF), respectively. It has two 8-inch diameter ports for connecting to the MPD nozzle and to the reducer adapter connected to the 4-inch gate valve; four 4-inch ports for diagnostics and measurements; two ports with quartz windows and two ports with regular glass windows. The interface of the test chamber is met with the MPD nozzle and the 4-inch gate valve.

e. Isolation Gate Valve.

Isolation of the hot gas flow is required for preventing the prematurely heated gas from leaking into the vacuum tank. Thus, a gate valve with water cooled gate, body, gate flange, bellows sealing, and actuator for large heat loads up to 1,000 ^{o}C was provided. Figure 10 details the isolation valve. Also a picture of the isolation valve is presented in Fugure 11. Two 4-inch ASA flanges, viton bonnet and gate seals, electropneumatic actuator, and stainless steel construction are designed with a position indicator. The flanges for both sides of the isolation valve are mated with the flanges of the test section and vacuum tank nozzle. The time required to fully open the gate valve is approximately 5 seconds. The other specifications of the gate valve are as follows:

Specifications	Description
Vacuum Level:	10^{-8} torr
Leak Test Sensitivity:	$1x10^{-10}$ STD cc/sec He
LeakRate (Max):	$1x10^{-8}$ STD cc/sec He at 10^{-3} torr
Sealing Pressure Differential (MaX):	15 psi/30psi optional
Orientation:	Any

Seal Direction:	Any
Soleniod Air Valve:	24 VDC/120 VAC Normaly Closed
Air Pressure:	75-125 Psig
Construction:	304 Stainless Steel/Mild Steel
Flange Configuration:	ASA/Copper Gasket
O-rings:	Viton/Buna-N
Auxially Equipment:	Spare Part List; Maintenence Manual; Installation Manual; Electric Schematic; Assembly Drawing.

f. Thruster Stand.

The thruster stand supports the thermal thruster chamber, the solar simulator arc-lamp, the elliptical reflector cavity, and the MPD thruster nozzle. It also allows the diagnostics and measurements possible on the thruster stand. The overall dimensions and functionalities are shown in Figure 12. Figure 13 shows a picture of the thruster stand with arc lamp head, elliptical reflector, and MPD nozzle. The height of the stand can be adjusted by 2 feet up and down, since the centerline of the nozzle is approximately 4 feet high from the floor. Two cooling water lines hook-up, a solar-simulator arc-lamp head assy with elliptical reflector, and flanges for quartz tubes are supported with the thruster stand.

g. Solar Simulator.

The solar simulator, Model 110 Lamp system, manufactured by Vortek Industries LTD. It is a DC Argon Arc, vortex stablized and liquid cooled system. The solar simulator has a role as a prime power source that release a solar flux-like spectrum for the STEP. This complex system provides (see Figure 14) approximately 60-kW optical power to the STEP thruster chamber continuously. The system selection and options were dependent on the interfaces of the elliptical reflector cavity, thermal thruster chamber, and MPD thruster nozzle. The arc size and power output requirements were determined by overall STEP system design. The arc lamphead is connected to a service cabinet that contains

the systems needed for operations. It consisted of electrical power supply, electrical control, gas pan components, lamphead assembly, and gas and water supplies.

1. Lamphead

The lamphead module contains a single 150 kW_e electrical input power arc lamp. The lamp produces optical radiation and operates continuously in high pressure argon gas. The arc is deionized water cooled, operates in DC and is vortex stabilized within a single quartz tube. Rapidly swirling water on the inner surface of the lamp tube efficiently removes exess heat and prevents deposition of electrode material. Assemblies at each end of the lamp house user-replaceable water-cooled tungsten electrodes. The following are characteristics of the arc:

- luminous flux	7.3×10^6 Lum.
- maximum radiative power	60 kW
- radiant flux intensity	500 W/cm^2.ster.
- color temperature	6,500 K
- spectral range	200 - 1400 nm,
- diameter	11 mm
- length	165 mm
- voltage (typical)	260 V
- current (typical)	575 A
- power input	150 kW_e
- gas	Argon

2. Service Cabinet

Cooling/Gas System

Deionized water and argon gas are recirculated, filtered and cooled in the cooling/gas system. A pump recirculates deionized water through a water-heat exchanger in a closed loop system for cooling the arc lamp.

Electrical Power Supply

The service cabinet houses a DC power supply, high-voltage ignitor and microcomputer-based controller (see Figure 14). The DC power supply consist of water cooled 3-phase SCR bridge rectifier with overload protection. The internal control system supervises start/stop

sequencing, current regulation, and fault monitoring along with providing an operator interface and servicing support. Operation of the lamp is fully automatic. Safety interlocks and an external computer interface are supplied as standard hardware. The operator has full control of start-up, shut-down and irradiance. The lamp head is located 15 ft from the power supply and service cabinet. All parts of the system replaceable and sell as replacement parts. Figure 15 shows a picture of the service cabinet.

h. Elliptical Reflector Cavity

The elliptical reflector cavity was designed to contain all the emissive power from the arc-lamp of solar simulator and to reflect and focus the optical power to the thermal chamber (see Figure 4). The optical power that the reflector handles is approximately 60-kW continuous power. The optical coupling efficiency of the elliptical reflector is approximately 0.6. The cooling systems of the elliptical reflector and side plates were designed to protect the reflective coating on the surfaces. The elliptical reflector has 2 parts, and each unit has two seperate cooling lines. The side plates are consisted of 4 parts which allows assembly with ease.

Package I Acceptance and Test

Package I was delivered to Hampton University on August 30, 1994. The solar simulator was delivered from Canada to Integra Tek, Inc. in May, but Integra Tek Inc was asked to pospone the delivery of the solar simulator and the other parts of Package I to Hampton University until August because the STEP facility was not completely ready at that time. The site installation of the solar simulator was done in October, 1994 by Vortek engineer Mr. Geoff Weitzer and technician Mr. So Ja during 4 days at Hampton. The cooling water systems for solar simulator and elliptical reflector were completed in September, 1994. Hence, the Vortek engineer and technician could successfully operate the lamp with elliptical reflector. They also trained the graduate research assistant Mr Dung Nguyen and post doctoral research associate Dr. Yoon Choi. The solar simulatoris ready for experimental use. The other parts of Package I were installed by an Integra Tek engineer in November, 1994.

Package II. Vacuum Pumping System

The required vacuum pumping speed was 3,000 CFM at 1 mtorr pressure. The vacuum pumping system manufactured by Kinney Vacuum,

Model KMBD-4501/KMBD-400/KD-50 Mechnical Booster System and consists of 3 stages :

The first stage is a Kinney Model KMBD-4501 Lobe Type Positive Displcement Blower. The blower cut in 2 torr, and continue to pump the system to 1-mtorr. The free air displacement is 4000 CFM, and the average pumping speed is 3000 CFM @ a speed 2700 rpm. The blower is complete with frame, V-belt, sheaves, guard, exhaust temperature switch, vacuum control switch, and a 20 HP, 3 phase, 60 Hz, and 230/460 volt TEFC motor.

The second stage is a Kinny, Model KMBD-400 Lobe Type Positive Displacement Blower. The blower cuts in 45 torr, and continues to pump the system to 2 torr before the above blower cuts in. The free air displacement is 400 CFM, and the average pumping speed is 275 CFM @ a speed of 3600 rpm. The blower is completed with frame, V-belt, sheaves, gaurd, exhaust temperature switch, vacuum switch, and a 3 HP, 3 phase, 60 Hz, 230/460 volt TEFC motor.

The third stage is a Kinney Model KD-50 Single Stage Rotary Piston Pump completed with base, sheaves, V-belt, belt guard, gas ballast valve, and a 2 HP, 3 phase, 60 Hz, 230/460 V, 1725 RPM TEFC motor.

The first and second stage blowers are water-cooled. The flow rate of water is less than 2 GPM at maxixum pressure of 100 Psig. Unit construction consists of two figure eight shaped rotors enclosed in a precision machined housing supported at each end by precision bearings. The power drive turns the drive rotor directly and rotates the driven rotor by means of specially forged, heat treated, crowned and ground precision helical gears. Efficient and effective vacuum pumping is accomplished by trapping a volume of gas at the booster inlet and between each rotor and the booster housing. This volume of gas is quickly and cleanly evacuated by the fast revolving rotors which carry the air to the exhaust side of the booster where the air is then discharged to backing pump.

Figure 16 shows the drawing diagram of the unit. A picture of the vacuum pumping system is shown in Figure (17).

The vacuum pumping system was delivered to Hampton University and installed on site on June, 1994. A housing for pump safety was bult in July, 1994 and the water cooling part for the pump system was completed in September, 1994. The pumping system is ready for operation.

The flexible interconnection between the vacuum pumping system and vacuum tank consists of a 12 inch diameter 30 inch length flexible bellows, 304 SST construction with ASA flanges, and a 12 inch port 304 SST gate valve construction with O-ring sealed and electro-pneumatic actuation, and a reducer adaptor, 1 ASA flange, 10"-length and 304 SST construction to mate to vacuum tank and gate valve. The interconnection parts were made by GNB Corporation and delivered to Hampton University in May, 1994.

Figure 18 shows a picture of Interconncting monifolds.

Package III. Vacuum Tank

A vacuum expansion tank of the capacity of 30 m^3 and a vacuum pressure of less than 10 mtorr was designed and manufactured by the Modern Welding Company. The tank is fabricated from SA-516-70 material with 0.5-inch thickness, was certified by ASME and warranty of equipment against defects and material for one year from the date of dilevery . Figure 19 shows desined drawing of the tank. A 3-step concentric reducing tubes connect the STEP thruster nozzle to the vacuum tank. The reducers allow the exausted from MPD nozzle propellant to expand into the tank continuously. To prevent corrosion on the outside surface of the tank, the surface was sandblasted and coated with oxide primer and enamel. The interior of the tank was also sandblasted. The tank is supported by two 6-inch hieght lifting lugs. The tank was transported from Georgia to Hampton University in June, 1994. Figure 24 shows a portion of the vacuum tank.

The vacuum tank was tested for leaks by the Southern Electric International Company on site at Hampton University on July 19, 1994. The rate of the leak was less than 11 millitorr in an 8 hour period on 7/20/94.

Package IV. Thermal Imaging System

A thermal imaging system, Model 600L, was purchased from Inframetrics Corporation. The Model 600L IR Imaging Radiometer is designed for applications requiring accurate real-time analysis of static or dynamic thermal patterns. The high performance system combines superior image quality and thermal sensitivity with the temperature measurement display, and automatic emittance and background correction. It could be used with a video cassette recorder (VCR) to

record thermal events in either color, or black and white for later analysis on playback. The system could also be interfaced with a computer or with an external thermal image processing system. A picture of the system is shown in Figure 20.

Other notable features of the Model 600L include five primary operating modes, a calibrated gray scale, eight color palettes, a 4:1 continous electro-optic (E-O) zoom, area display, and remotely controlled optical filter. This unit additionally calibrated to measure up to 3000 ^{o}C. Since this unit was a demo-, and discontinued model, its price was reduced to 50% of the quoted price. The following are other specifications:

- Spectral Bandpass	8-12 μm
- Detector	(HgCdTe) @ 77 K
- Detector Coolant	Electrically cooled
- Scan Rate	8 kHz Horizontal; 60 Hz Vertical
- Output Rate	15,750 Hz Horizontal; 60 Hz Vertical
- Field of View	15^{o} Vertical x 20^{o} Horiz.
- Temperature Measurement Range	0^{o} to $1500^{o}C$
- Spatial Resolution(50% SRF)	2.4 mRad, 148 IFOVs/Line
- Dynamic Range	7 Bit
- Active IR Lines/Frame	200
- Display Resolution	400 Lines/Frame
- Emittance and Background Correction	
- Data Acquisition Mode	
- Automatic Parameter Recovery System	
- Direct Temperature Readout:	Fixed Area Display Point Mode Isotherm
- Emittance Measurement Mode	
- 4:1 Continuous E-O Zoom	
- Remote Focus	

The system was deliverd to Hampton University in August, 1994. The purchase of the system included a free training course by the Inframetrics. The training course is scheduled for the graduate research assistant, Dung Nguyen, in January, 1995.

Package V. Data Acquisition System

A data acquisition and control system for the experiment of STEP was developed by Nondeterministic System Corporation. The system provides at least 20 analog inputs required for the following measurements and control outputs:

- Measurement of supply temperature and pressure at coolant return.
- Measurement of temperature and pressure at the booster pump.
- Measurement of helium temperature, pressure, and flow rate.
- At least 3 temperature measurements for the solar simulator.
- The capacity of making six temperature measurements and a pressure measurement for the test section.
- Measurements and control for the management of two gate valves; one at the interface between the nozzle and vacuum tank, and one at the interface between the vacuum tank and the tank's vacuum pump. These valves will each require a discrete signal for opening/closure, and a measurement of feed pressure.
- Finally, a flow speed measurement at the nozzle via a doppler laser velocimeter is planned.

In addition, a facility for logging and storing the data commands from the experiment, and signal conditioning and isolation at the front end of the system were required.

According to the above requirements, a data measurement and control system Model NSC-0011a and Data measurement and control system support module Model NSC-0011b was purchased. The detailed specifications for each model are as follows:

The NSC-0011a has 12 bit resolution throughout, 15 non-amplified analogs, 16 amplified analogs (suitable for thermocouples), 2 analog outputs, 16-channel TTL-compatible digital I/O, and a programmable interval counter/timer. Other specifications are:

Main Analog Input

Channels: 15 single-ended — Resolution: 12 bits

Conversion Speed: 25 μsec — Accuracy: 0.015%

Analog Output

Channels: 2 channels — Resolution: 12 bits

Settling time: 30µsec Output driving: 5 mA max
Output Range: 0 to +5V with internal reference,
0 to +10V with external reference.

Digital Input
Channel: 16 channels
Level: TTL, compatible, input low 0.8V min, input high 2.0 V min.
Input loading: 0.4 mA max at 0.5 V (low), source 0.4 mA at 2.4 V output.

Programmable Timer/Counter
Device: INTEL 8253 Pacer Output: 35 min, pulse to 500kHz
Time Base: 2 MHz

The NSC-0011b supplies support functionality for the NSC-0011a data acquisition and control system. The desktop unit includes mounting hardware for the NSC-0011a, keyboard/mouse command interface, graphical display, and high-speed and archival data storage. Other specifications are:

Data Storage
High speed storage: 400 Mbytes
Archival storage: 120 Mbyte mini-data cartridge tape

Graphical Display
Color-SVGA, with 14-inch diagonal measurement

Data Acquisition/Control Software Enviroment
Labtech™ , providing Graphycal User Interface(GUI) display and editing of data acquisition system settings, functions, and measurements. This system was customized to met the requirements of Hampton University's STEP experiment.

The data acquisition system will be delivered to Hampton University for installation and operation in December, 1994.

Mass Flow Controller

The mass flow controller include: pressure regulators for argon, helium and nirtrogen gases; mass flow controler; mass flow meter; pressure transducers; termocouples. The instruments under this category were purchsed from different industries according to the requirements. The specifications for each instrument are:

1. Three "two stage regulators" model E-12-A-144D 580 with maximum pressure of 200 psi provided by Air Products & Chemical, Inc. for all gases.

2. Pressure transducer 0-75 psig, 4-20 mA out with a digital process meter model PD 690, provided by Keller Psi Co.

3. Mass flow meter Model HFC-202A, 0-500 SCCM of Helium with power supply Model 200, provided by TBE-Hastings Instruments.

3. Mass flow controller Model HFC-203C, 0-300 SLPM calibrated for Helium gases, with a four channel power supply Model 400 provided by TBE-Hastings Instruments.

4. Differential pressure transducer at 0.5 in H_2O Model 223BD-00001ACU-S with Model 660A10 power supply/display provided by MKS Instruments, Inc.

5. Absolute pressure transducer from 0-100 Psi Model 122-AA-05000BB-SPCAL with Model PDR-1 power supply provided by MKS Instruments,Inc.

6. Absolute pressure transducer from 0-100 Torr Model 122AA-00100AB with Model PDR-D-1 power supply provided by MKS Instruments, Inc.

7. High temperature thermocouple:Model XMO-W5R26-U-125-30-B-1 Exotic probe maximum operating temperature 4000 F with Model DP81T digital thermometer provided by OMEGA Engineering, Inc.

All items of the mass flow controller were delivered and are being installed.

Other equipment

1. Refrigerated Cooling Unit

A refrigerated cooling unit with deionizer train was required for circulating cooled water around the thermal chamber. A Model RW-400 Series Cooling Unit with the following specification provided by Electra Impulse, Inc. Figure 21 shows a picture of this unit.

- Flow rate 4 gal/min

- Capacity	4.5 GA.
- Pressure	65 Psi
- Power	208 V, 3 phase, 60 Hz

2. Lincoln Welding Power Supply

This power supply was required for the MPD channel of a top-table prototype thermal electric propulsion system. This power supply was purchased from the local Home Quarter Store. The specifications for the Model PAK-125 power supply are:

- Input	230V/60Hz/20A
- Output	130A/20V/25%
- Operating Voltage	33VDC

3. Air Compressor

An air compressor of Model 1528IN , 6HP, 120 Psi, and 60 Gallon capacity was purchased from the SEARS, Inc. This air compressor was required for providing air pressre of 75-100 Psi to activate the both gate valves. Figure 22 shows a picture of the air compressor.

Renovation and equipment installation

1. Outdoor Cooling System

A water circulated cooling system with a flow rate of 25 gal/min and a maximum pressure of 40 psi was required to remove the excess heat produced in the solar simulator during the operation. Figure 23 shows the layout of the cooling system and Figure 24 presents its picture. Design and construction of the cooling system was contracted with Integra Tek, Inc. The system is consisted of 6 radiators, 6 fans with electric motors, a 270 gallons capacity water tank, a booster pump of 80 psig capacity and pressure and temperature gauges. The system is supplied with 50% deionized water and 50% antifreeze.

2. Facility renovations

A contract for the renovations, adequate electric power and water supplies in Room 100 of Armstrong Slater for the support of the STEP research project was done with The Livas Group Architects. The contractor provided adequate concrete floor, concrete footings and building slab for vacuum pumping system and vacuum tank outside the

room, housing for vacuum pump, plumbing and electrical power. The total cost of this order was $66,750. An amount of $32,000 was paid by the University and the remainder of $34,750 was paid through the Grant.

3. Electric Power

The major STEP electrical components required 3 phase 240 volts electric wirings. A total of about 250 kW_e electrical power was considered for the entire STEP facility. The major power consumptions are:

- Solar simulator arc lamp 150 kW_e (Max.)
- MPD power supplies 52 kW_e (max)
- Vacuum pumping system 16 kW_e

A contract for the electrical job was issued to the Arrow Electrical Inc. through the Livas Group Architects, P.C., the Hampton University contractor for facility renovations. The renovation and electric wirings were completed by the end of September, 1994.

The STEP equipment installation was completed by October 30, 1994 and ready for test experiment.

Conclusion

Under AFOSR Grant #F49620-93-1-0611 for the development of an advanced thermal and electric propulsion system, the solar TEP or STEP system, chosen for experiment, was acquired in five packages: a thermal and an MPD thruster nozzle with a test section, including, a solar simulator (argon arc lamp); a vacuum pumping system; a vacuum expansion tank; a thermal imaging system; and data acquisition system. These subsystems have been procured, installed and tested on schedule. The complete system operation is now possible and diagnostics systems are now under installation.

To date, the formation of the research team is near complete. The team is supported under a separate AFOSR Grant #F49620-94-1-0263 for operation and diagnostics of the STEP system to establish proof of the STEP concept.

References

[1] Selph, C. C. "The Place of Solar Thermal Rockets in Space", Proceeding of 1981 JANNAF Propulsion Meeting, CPIA Publication 340,Vol. II, pp.265-288, May 1981.

[3] Sager, P. "A Comparison of Nuclear Propulsion Systems with Chemical Rocket Aerobrake System for a Mars Transfer Vehicle", AIAA-91-2334, AIAA/SAE/ASME/ASEE 27th Joint Propulsion Coference, June 24-26, 1991.

[3] Mueller, J. and Micci, M. M. "Microwave Electrothermal Thruster Using Waveguide Heated Plasma", AIAA-90-2562, AIAA/DGLR/JSASS 21th International Electric Propulsion Conference, Orlando, Fl, July 18-20, 1990.

[4] Bagher M. Tabibi, Sang H. Choi, and Ja H. Lee "Thermal-Electric Propulsion with Magnetoplasmadynamics Acceleration" AIAA-94-2468, 25th AIAA Plasmadynamics and Lasers Conferance, June 20-23, 1994.

[5] CRC Handbook of Table for Applied Engineering Science, 2nd Ed., p. 121,1972.

[6] Sala, A. "Radiant Properties of Materials", table of radiant values for blackbody and real materials, 1986.

STEP equipment Costs

Item	Estimated Cost	Item/Substitution	Actual Cost
Solar Simulator	$150,000	SolarSimulator Arc Lamp, Power Supply, gas and water Supplies and Electronics.	$150,000
		Refrigerated Cooling Unit with Deionized Train.	$7,450
		Solar Simulator Cooling System.	$6,000
		$163,450	
Elliptical Reflector	$13,000	Elliptical Reflector	$13,000
Thruster Chamber	$30,000	Thruster Chamber	$30,000
MPD Thruster Nozzle	$20,000	MPD Thruster Nozzle	$20,000
MPD Power Supply	$5,650	MPD Power Supply	$5,650
Thruster Stand	$8,000	Thruster Stand	$8,000
Isolation Valves & Baffles. 16" Diam. 2 each	$20,000	One 4" Diam. Gate Valve	$7,000
		A s.s. Test Section with 6 Ports,Two Ports with Quartz Windows	$3,000
		$10,000	
Thermal Imaging System Model 600L	$68,500	Thermal Imaging System- Demo purchased as last available with this Model 600L.	$35,000
Expansion Vacuum Tank	$44,699	Expansion Tank	$44,699
Vacuum Oumping System	$47,875	Vacuum Pump	$32,375
		18" Gate Valve	$6,400
		Reducer Adapter 18" to 12"	$2,800
		Reducer Adapter 12" to 8"	$850

		Bellows 12" Diam.	$2,600
		O-Rings	$ 250
		$45,275	
Mass Flow Controller	$7,000	Mass Flow Meter.	$1,991
		Mass Flow Controller.	$2,358
		Pressure Transducer 0-75 psig with Digital meter.	$663
		High Temp. Thermometer, Maximum Operating 4000^{o}F with Digital Readout.	$804
		Differential Pressure Transducer with Power Supply.	$1,170
		$6,986	
Computer	$1,926	Data Acquisition System includes computer and 20 chennels analogs read-out and softwares	$7,940
Other Equipment	$0	Two Stage Pressure Regulator, 3 each for Argon, Helium and Nitrogen Gases	$624
		60 Gallon Air Compressor	$475
		Absolute Pressure Transducer, From 0-100 psia with power supply.	$1,515
		Absolute Pressure Transducer, From 0-100 Torr with Power Supply.	$1,250
		Lincoln Welding Power Supply.	$543.45
		$12,347.45	
Renovation	$15,000	Renovation, Electric Power, and equipment Installation.	$34,750

Grand Total: $ 429,157.45

Table 1 High Temperature Materials for STEP Thermal Chamber

Materials	Physical Properties			Chemical Properties			Other Information	
	Melting Point	Thermal Cycling	Rupture Stress	Oxidation	Nitration	Water Vapor	Mechanical Properties	Availability or In Use
Rhenium (Re) [1,4,5,6]	3180 C	Stable	1600 psi at 2500 C run 10 hrs	Re_2O_7 at 600 C melts at 297 C boils at 363 C Coating required	No Reaction	Promote Oxidation	Excellent ductility. Easy fab. Easy welding	Widely used: Rocket Chamber Crystal Growth
Tantalum (Ta) [1,2,6]	2996 C	Moderate	90 % reduction at 1000 C	Starts at 250 C	Ta_2N at 2100 C	NA	Cold forming Easy fab.	Widely used. Mechanical parts
Tungsten (W) [1,2,3,6]	3390 C	Moderate	50 % reduction at 1000 C	Starts at 400 C and rapid oxidation at 500 C	WN_2 at 2300 C	Promote Oxidation at 500 C	Poor ductility	Machine tools
Iridium (Ir) [1,4]	2455 C	Moderate	NA	at 1150 C	No reaction	NA	Excellent ductility	Crucibles Crystal growth

Reference:

[1] Shaffer, P. T. B.: Plenum Press Handbooks of High-Temperature Materials, Vol. 1. Plenum Press, 1964.

[2] Brown, W. F.: DOD Aerospace Structural Metal Handbook, Vol. 5, CINDAS/Purdue University, 1992.

[3] Kohl, W. H.: Handbook of Materials and Techniques for Vacuum Device, Reinhold Publishing Co. 1967.

[4] Carien, J. C.: Company Catalog, Sandvik Rhenium Alloys, Inc. Elyria, Ohio, Tel: (216) 365-7388, 1993

[5] Kangilaski, M.: Company Catalog, Martin Marietta Space Power, San Jose, CA, Tel: (408) 365-6316, 1993

[6] Tuffias, R.: Company Catalog, Ultramet Co., Pacoima, CA, Tel: (818) 899-0236, 1993

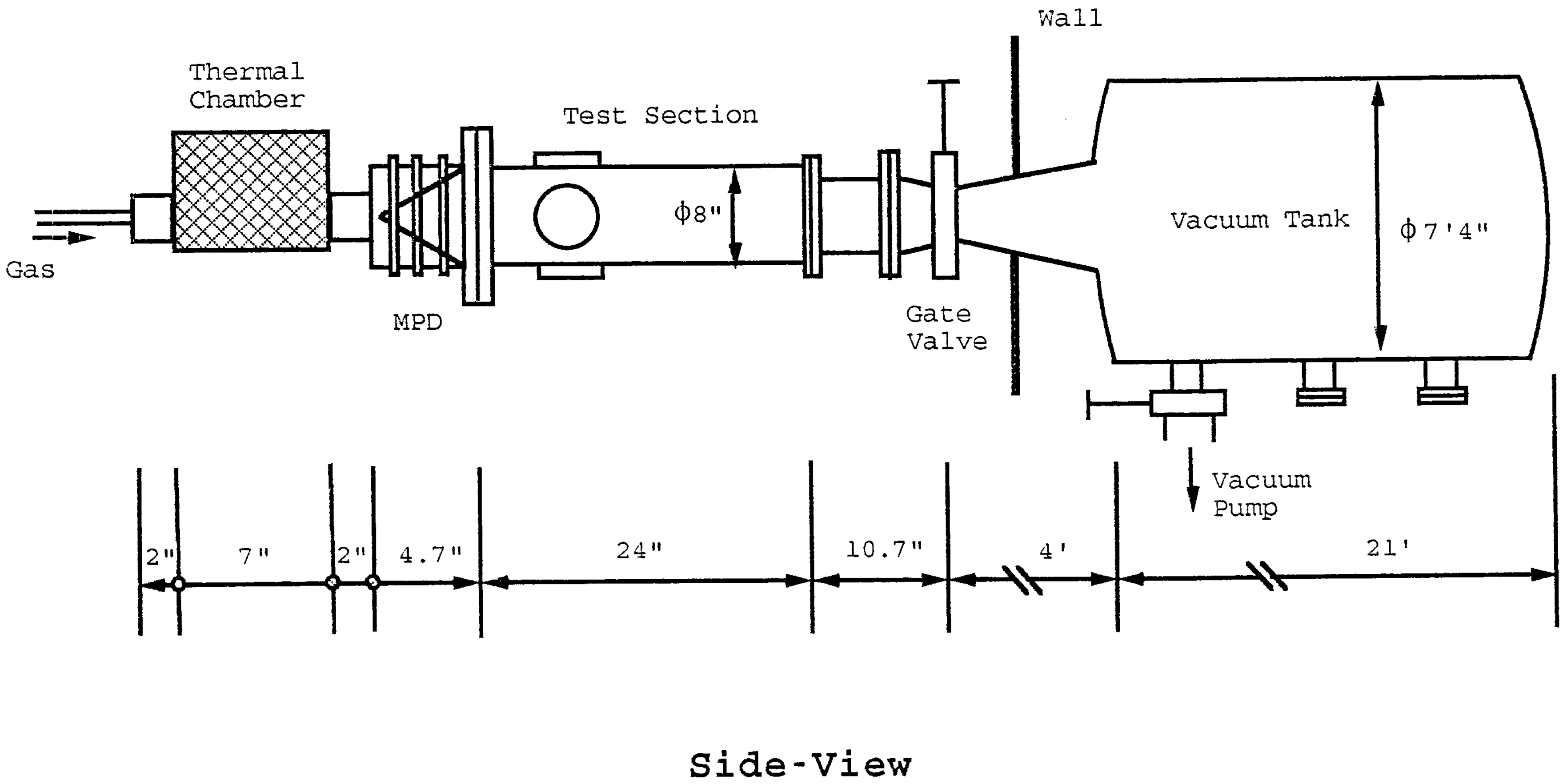


Figure 1. Schematic of TEP Facility Setup (Hampton University)

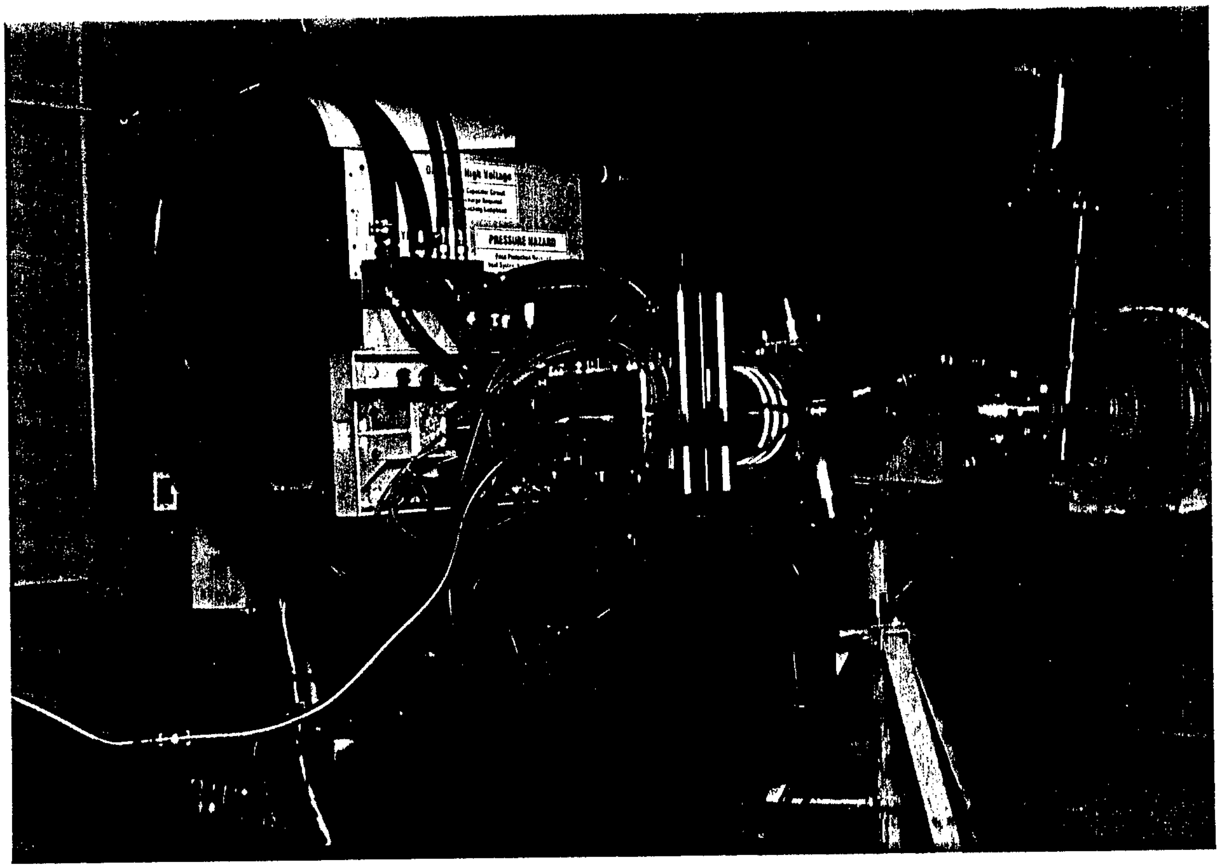


Figure 2. A picture of the indoor part of the STEP.

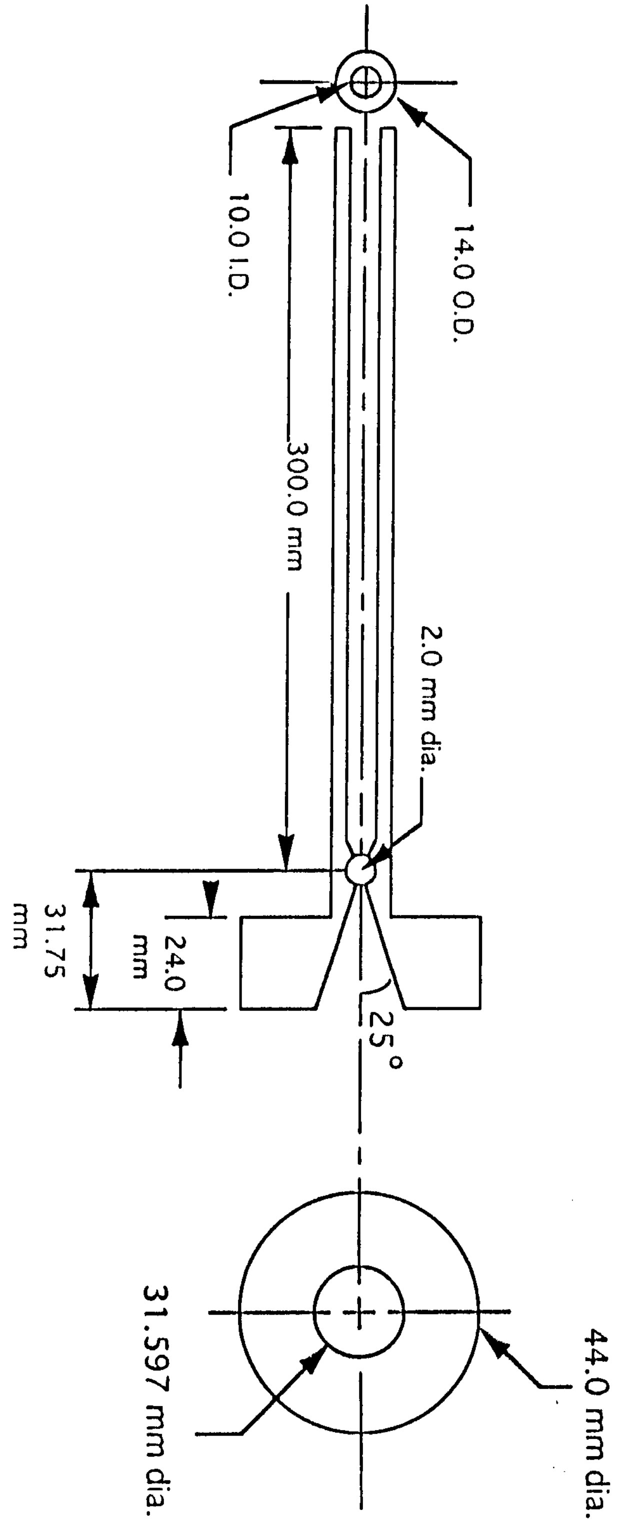


Figure 3. The dimensional diagram of the thrust chamber.

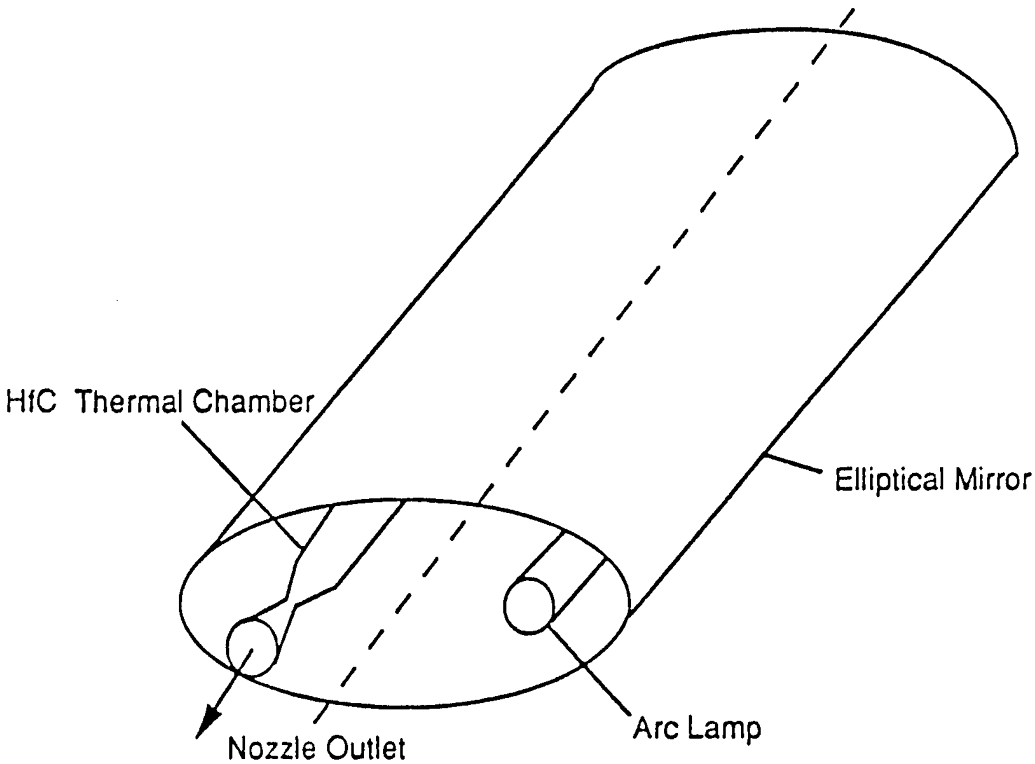


Figure 4. Elliptical cylindrical reflector arrangement for solar simulator arc lamp and thermal chamber housing.

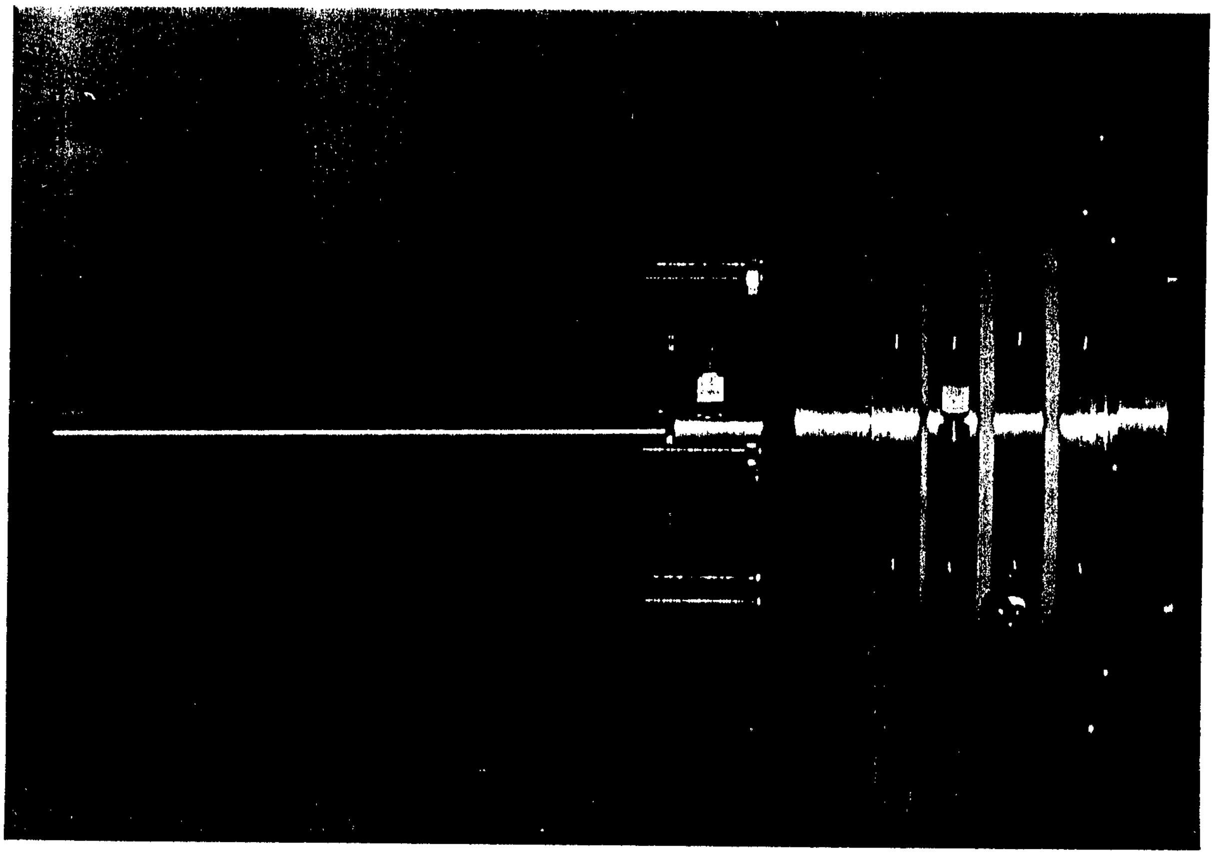


Figure 5. A picture of the thermal chamber with the MPD thruster nozzle.

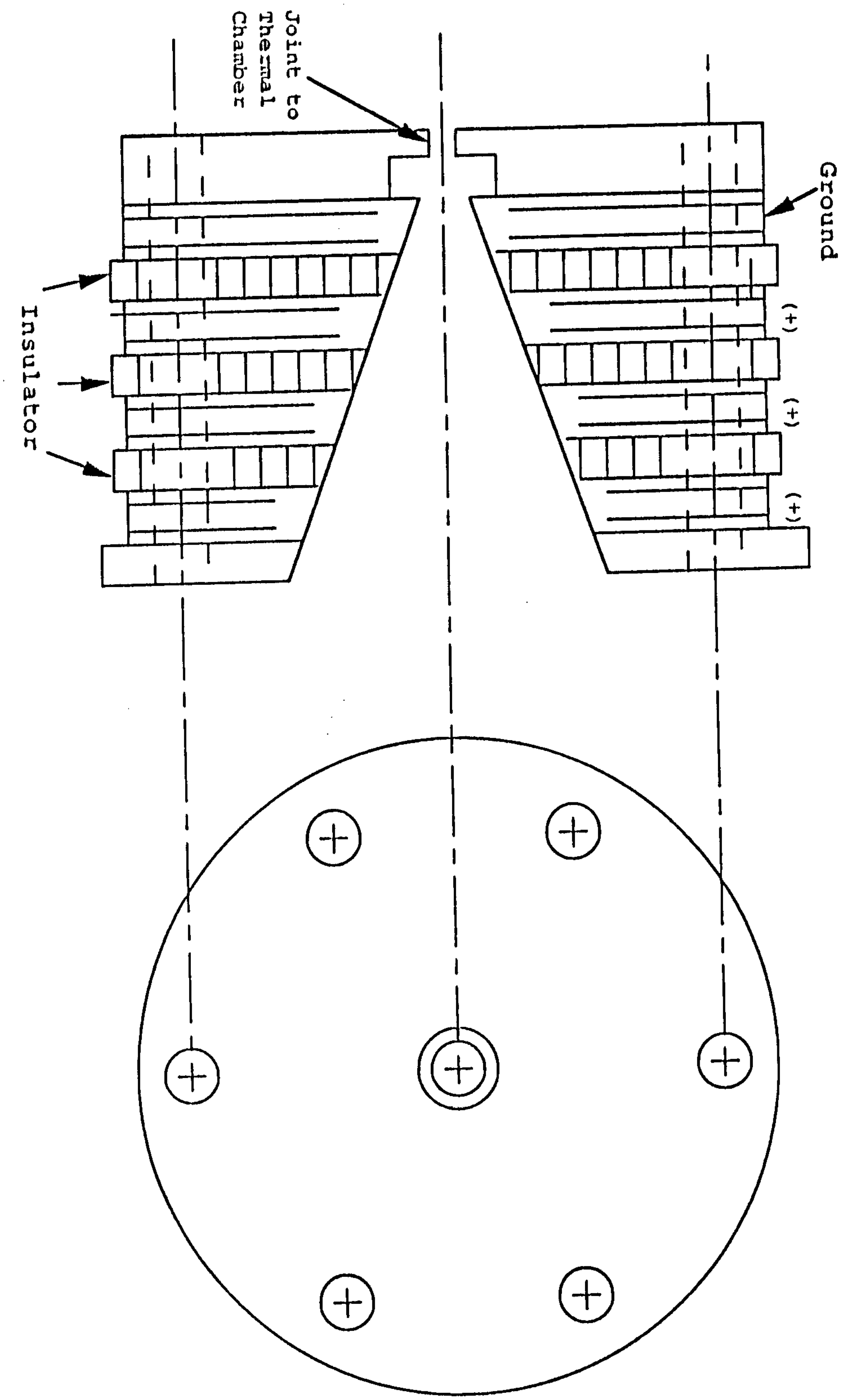


Figure 6. The MPD thruster nozzle diagram.

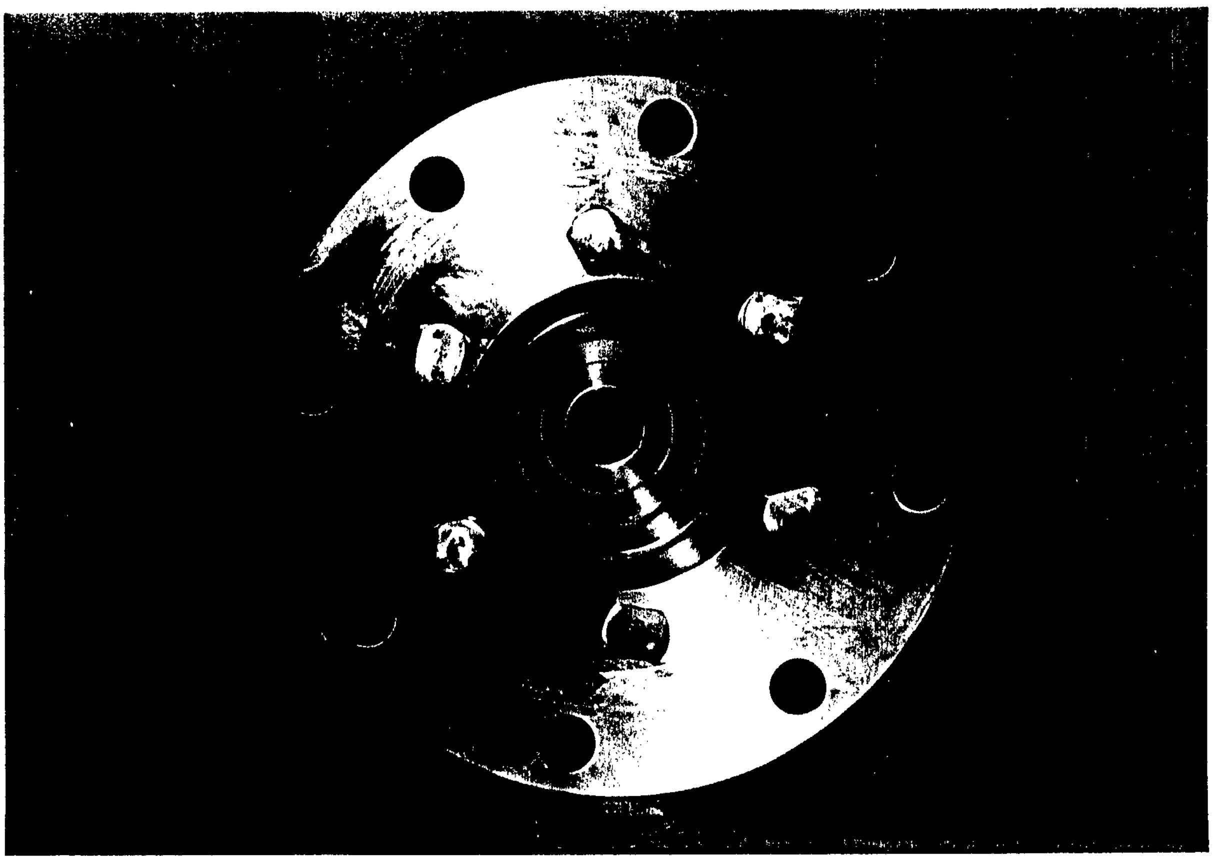


Figure 7. A picture of the MPD thruster nozzle.

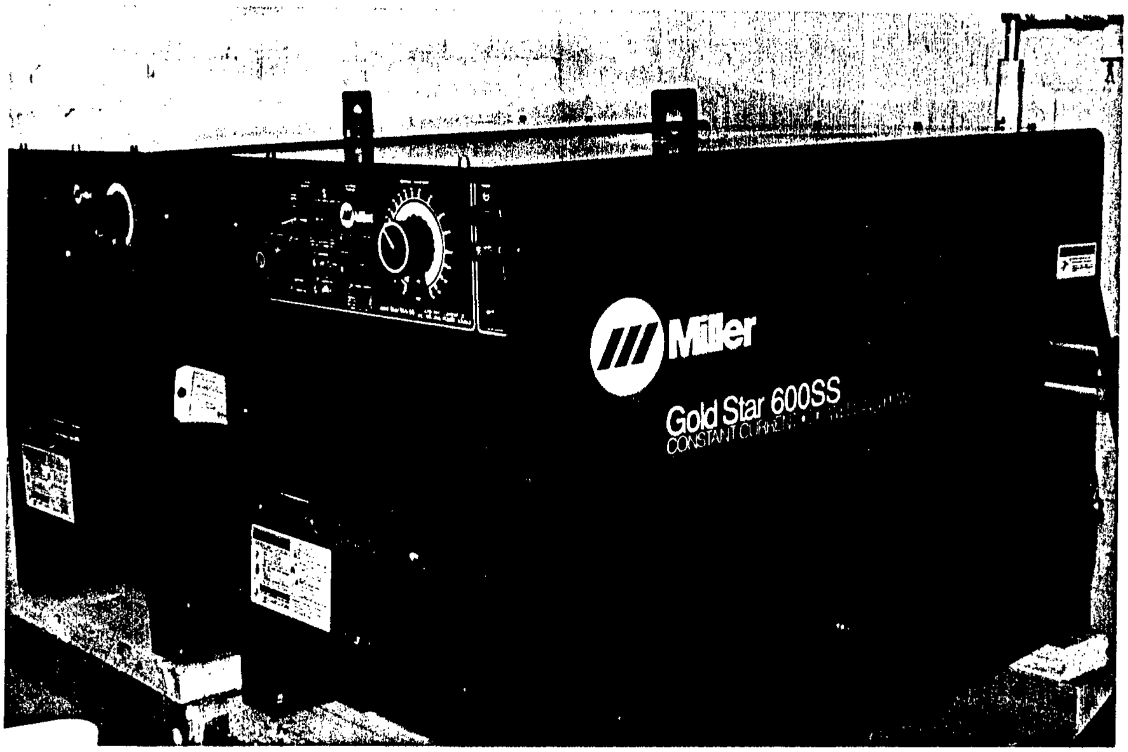


Figure 8. A picture of the DC power supplies.

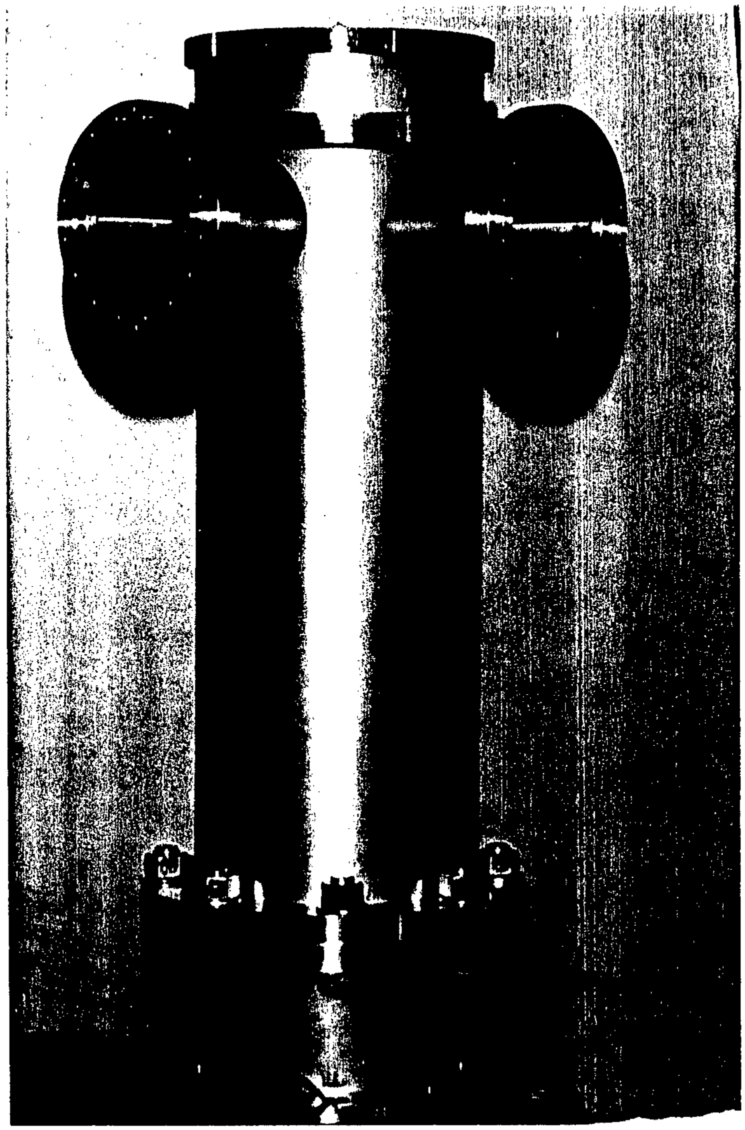
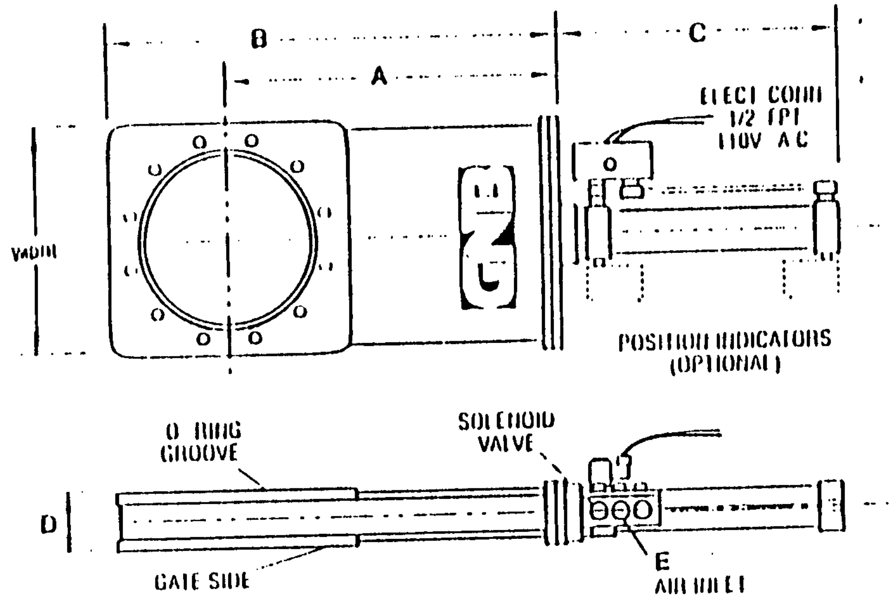


Figure 9. A picture of the stainless steel test section.

Electro-pneumatic

Stainless Steel
Position Indicator



I.D. : 3.38
Max. Width : 7.50
Bolt Circle : 6.00
Hole/Size : (4) 0.625 - 11
Valve Dimensions (inches):
A = 7.750
B = 11.50
C = 9.750
D = 3.50
E = 0.250
Approx. Wt (lb) : 34

Figure 10. Schematic diagram of the isolation gate valve.

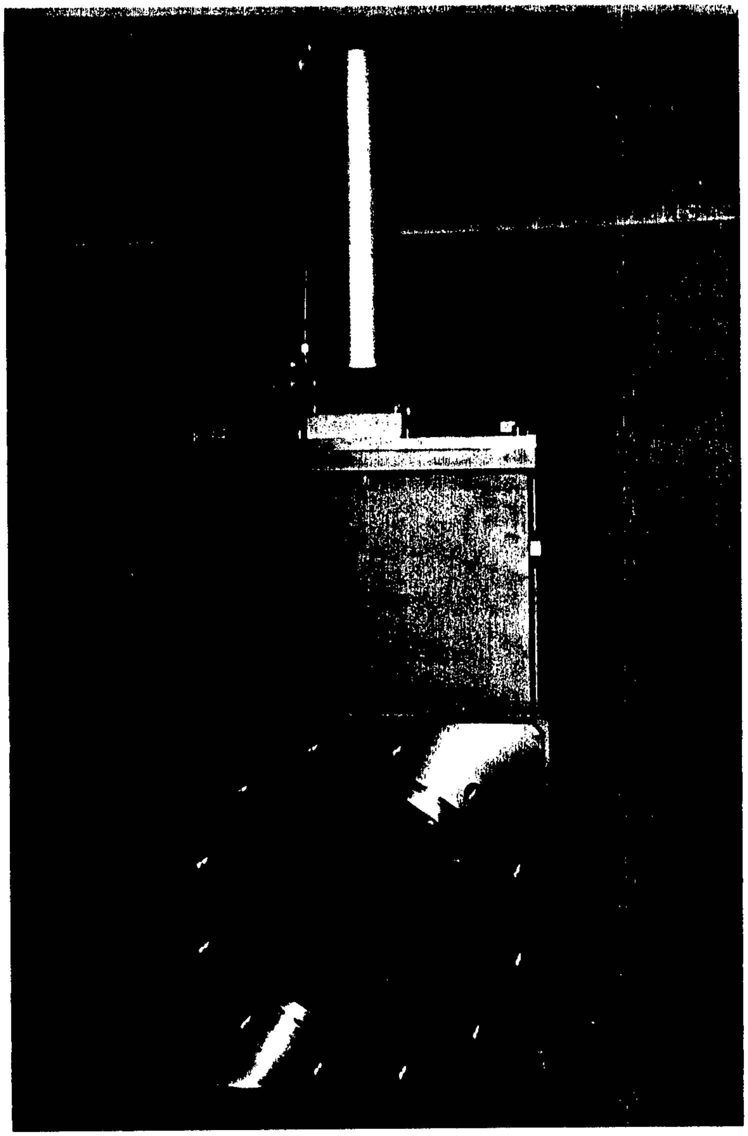


Figure 11 A picture of the isolation gate valve.

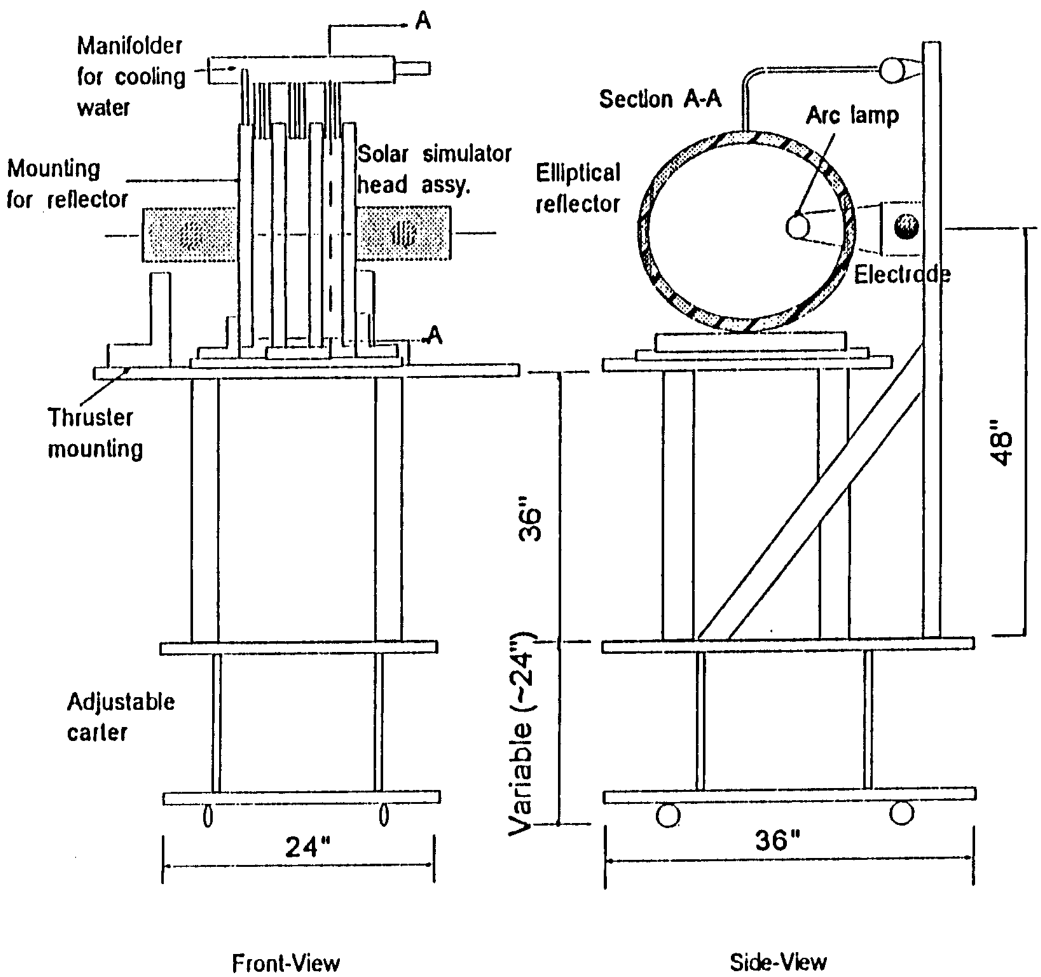


Figure 12. Dimensional diagram of the thruster stand.

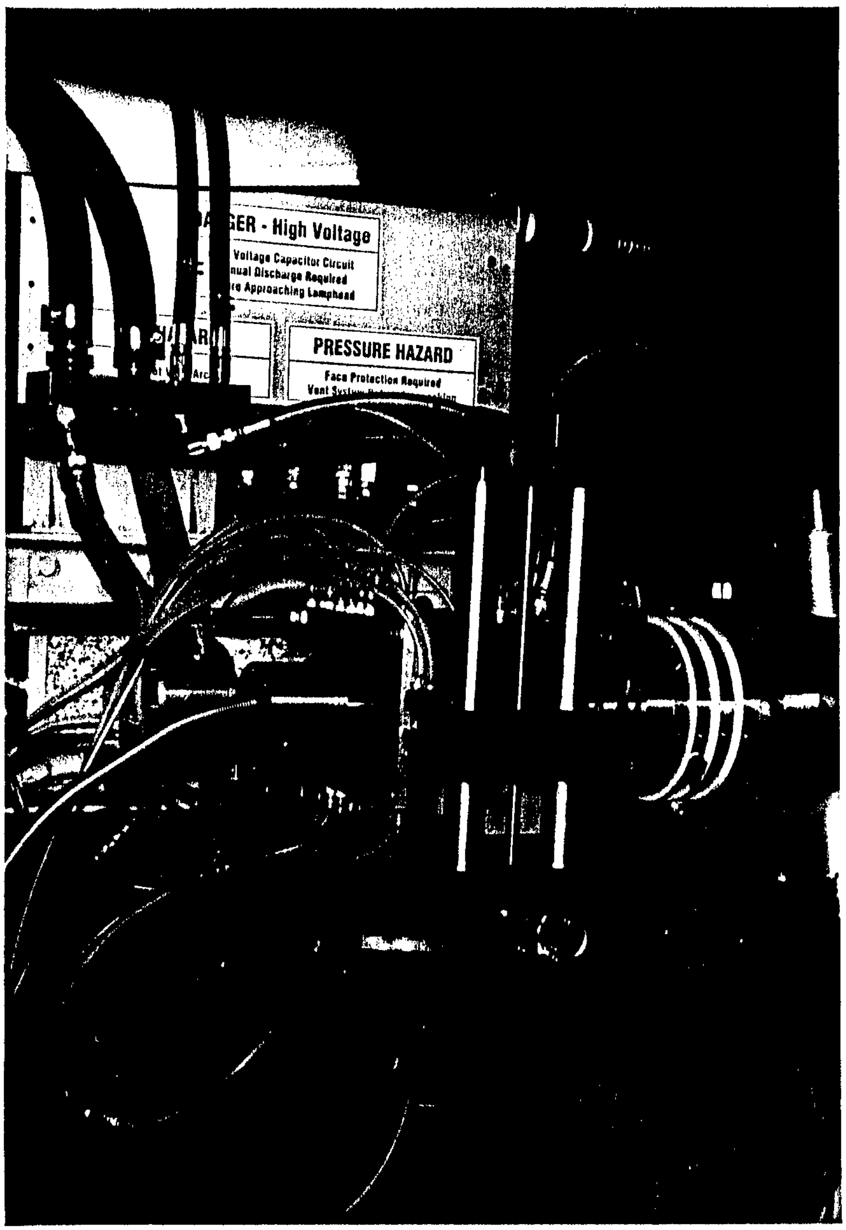


Figure 13. A picture of the thruster stand with the arc lamphead, elliptical reflector, and MPD nozzle.

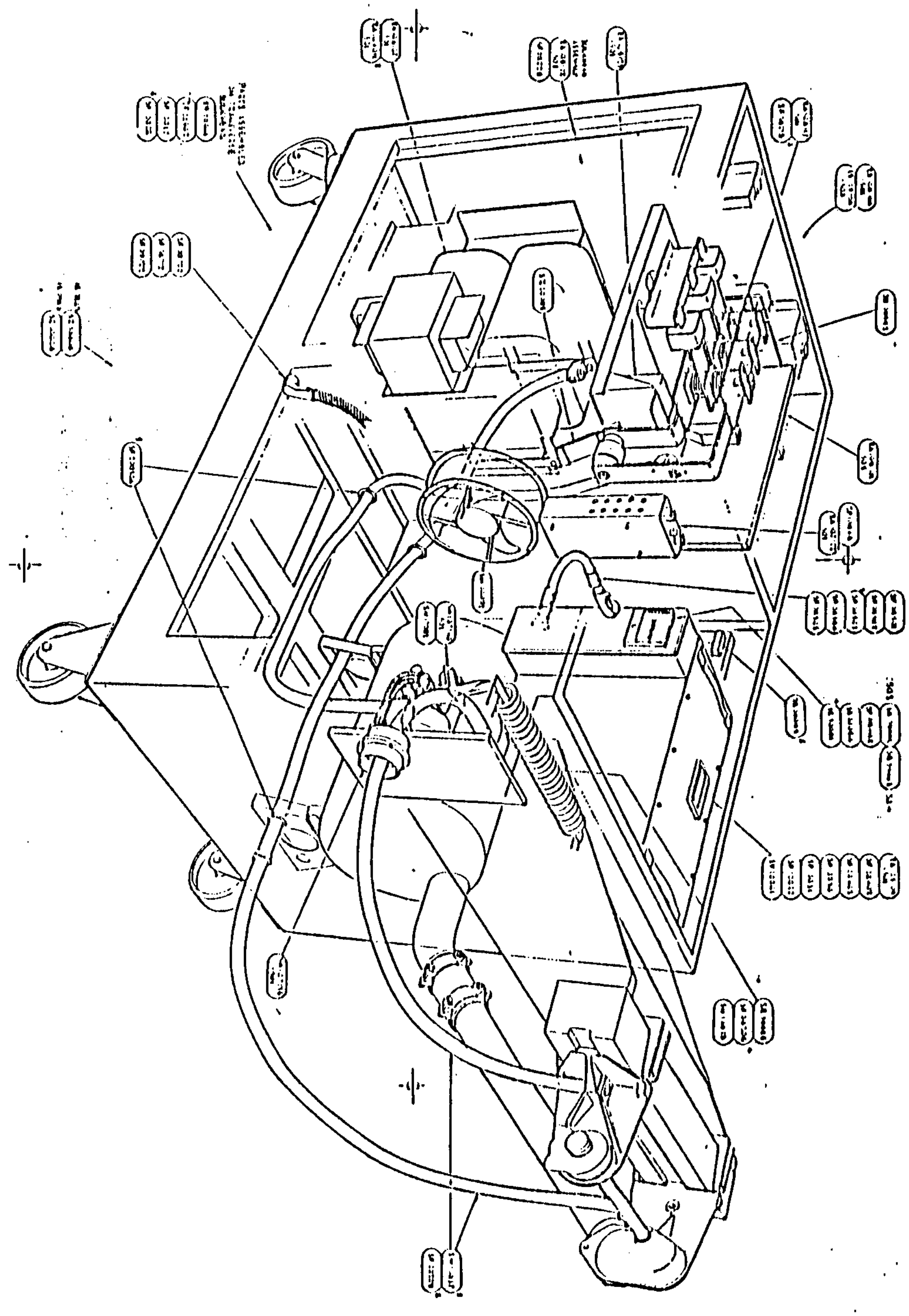


Figure 14. Schematic diagram of the solar simulator arc lamp system.

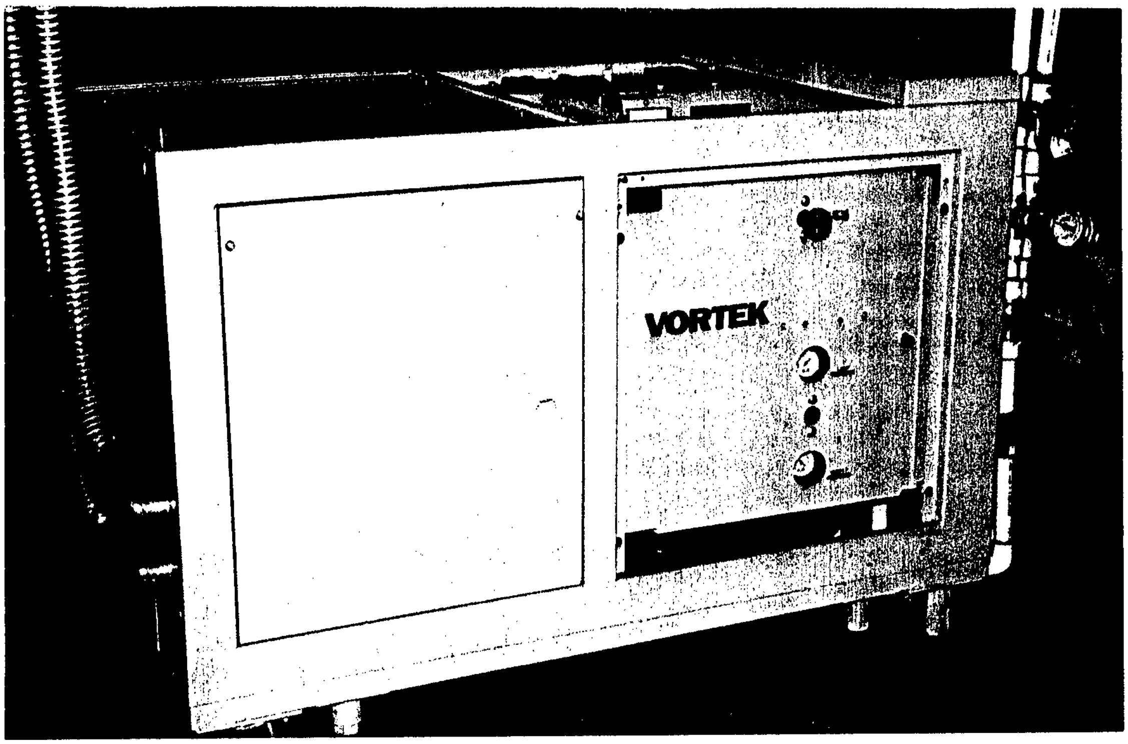


Figure 15. A picture of the solar simulator service cabinet.

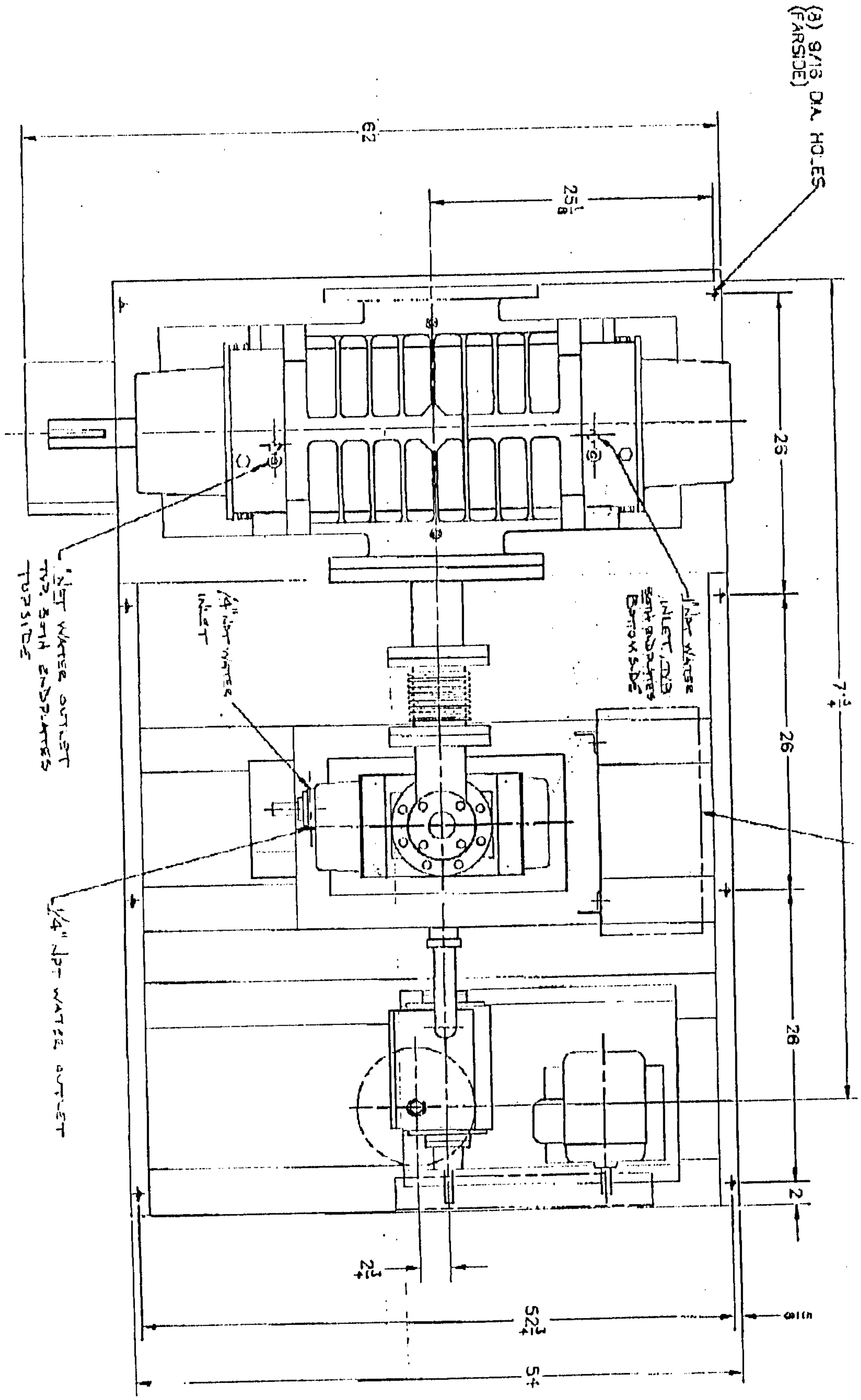


Figure 16. Schematic diagram of the vacuum pumping system.

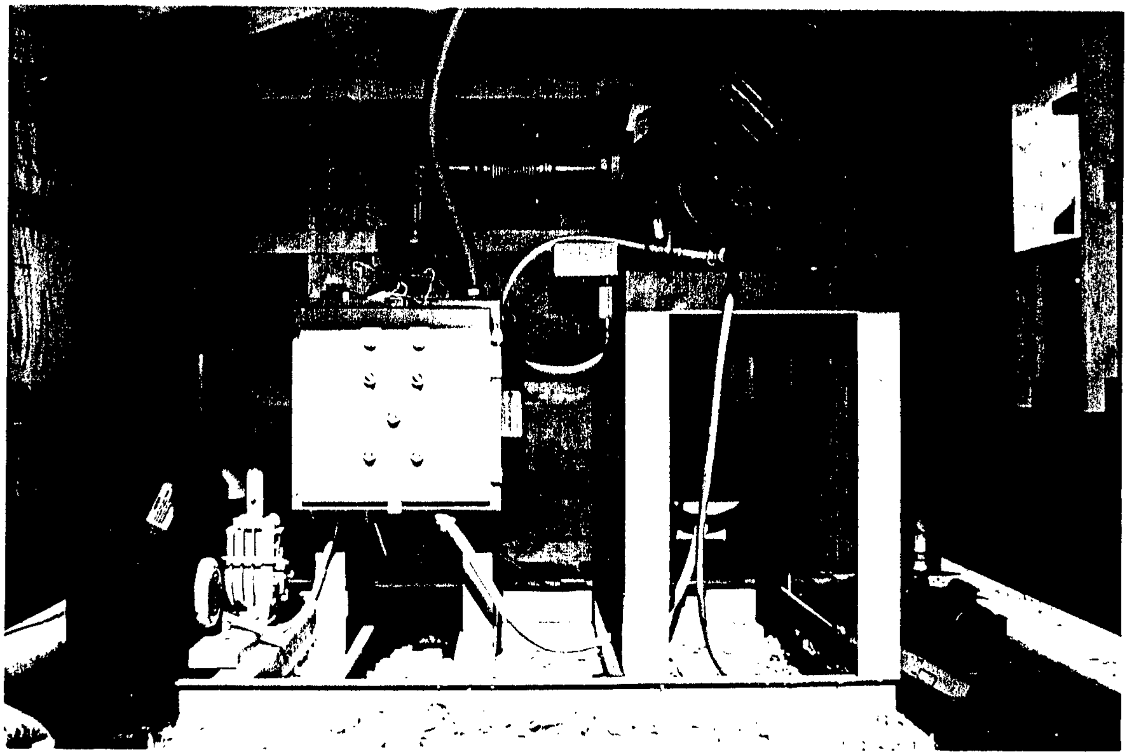


Figure 17. A picture of the vacuum pumping system.

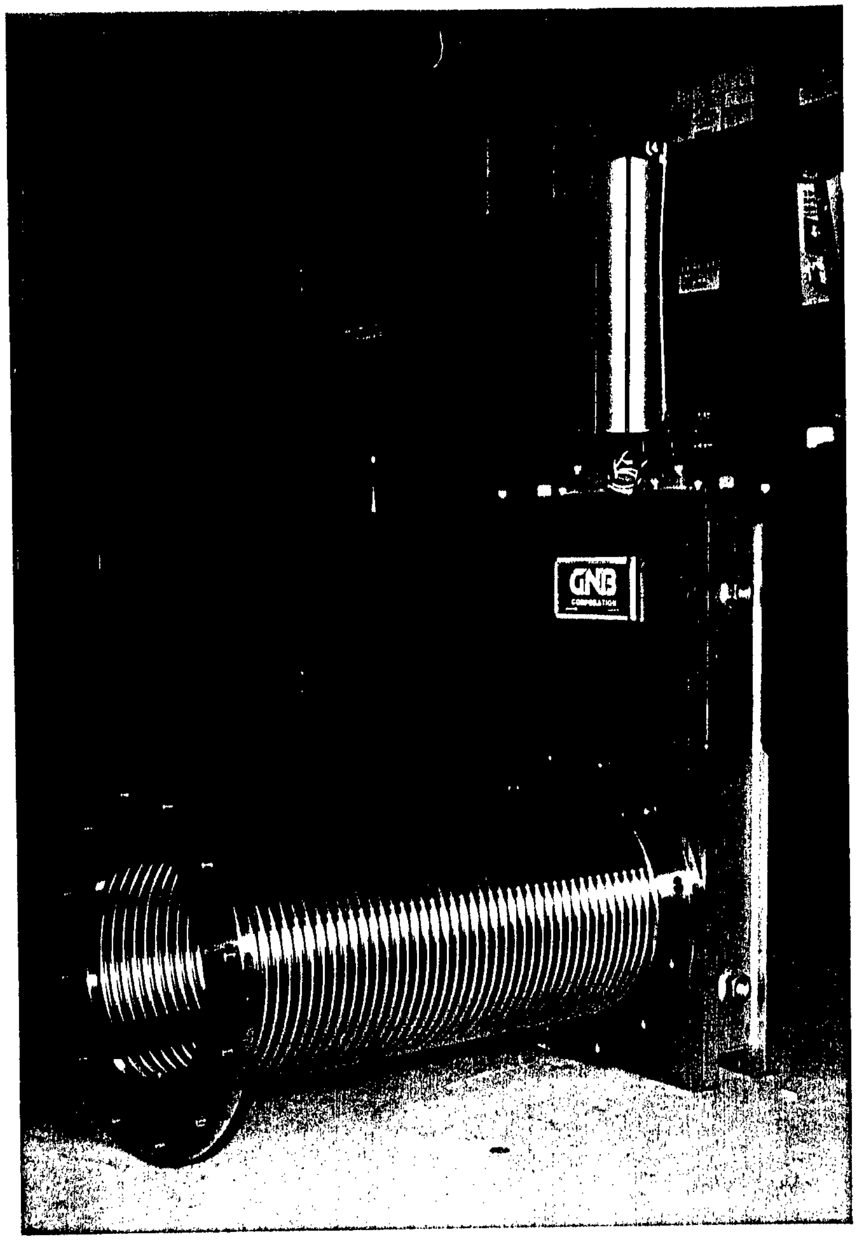


Figure 18. A picture of the interconnecting monifold of vacuum pump and vacuum tank.

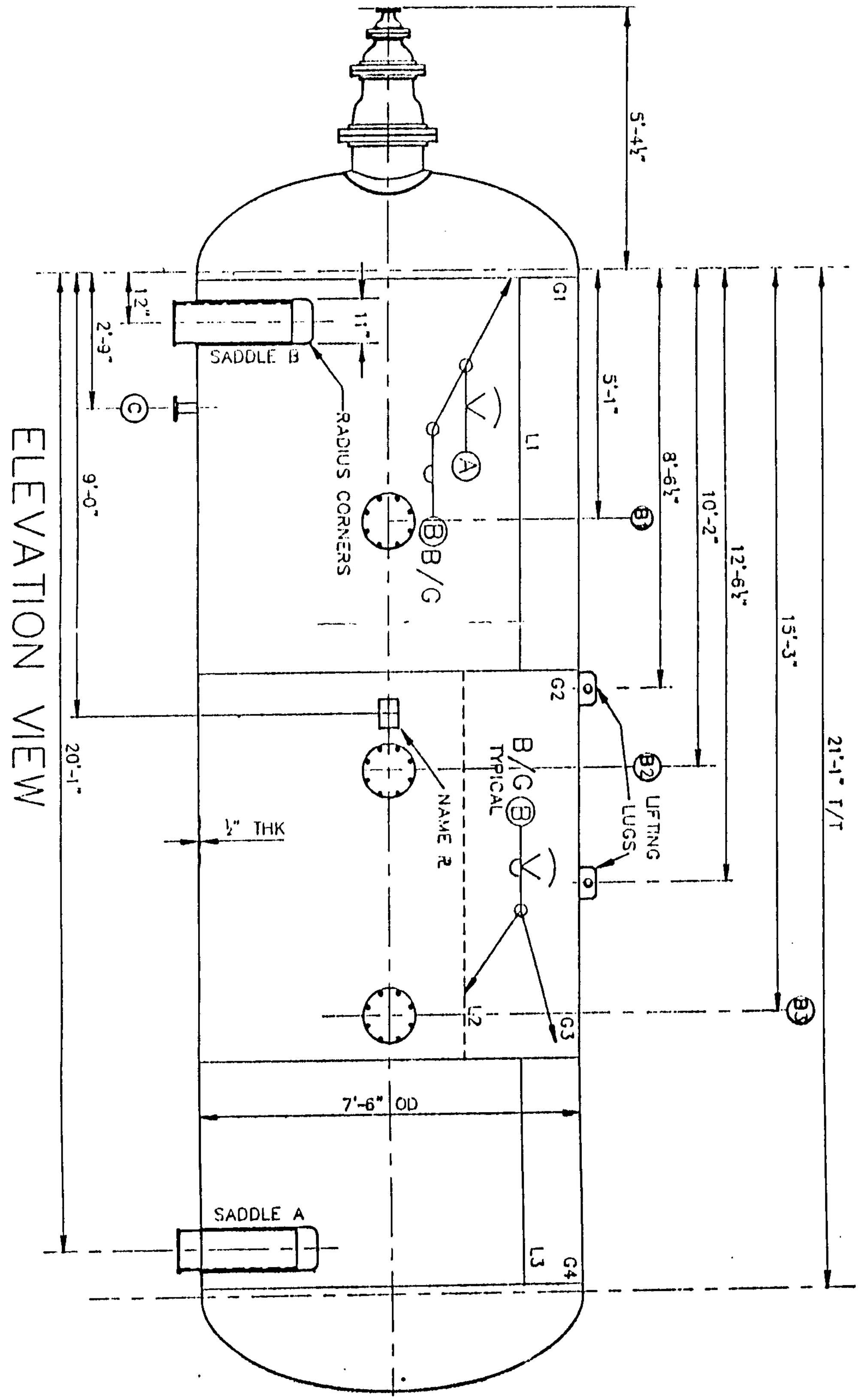


Figure 19. The dimensional diagram of the vacuum tank.

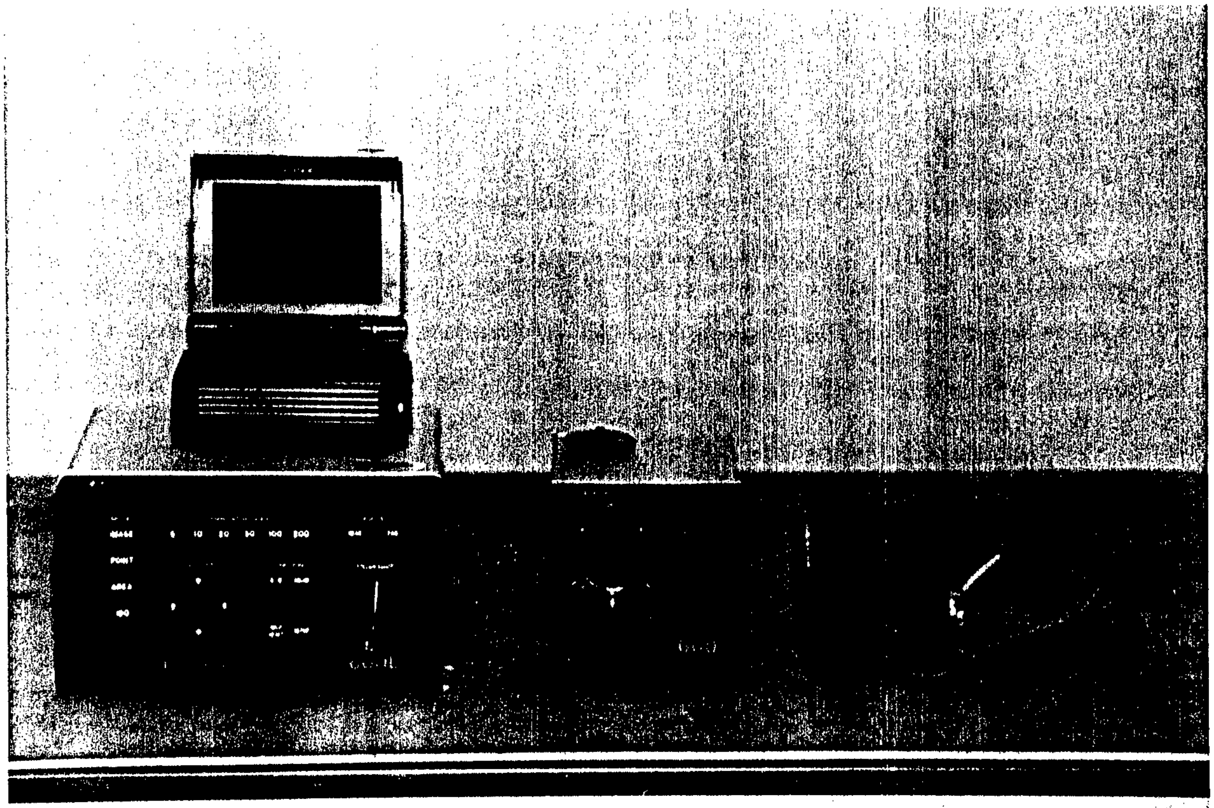


Figure 20. A picture of the thermal imaging system.

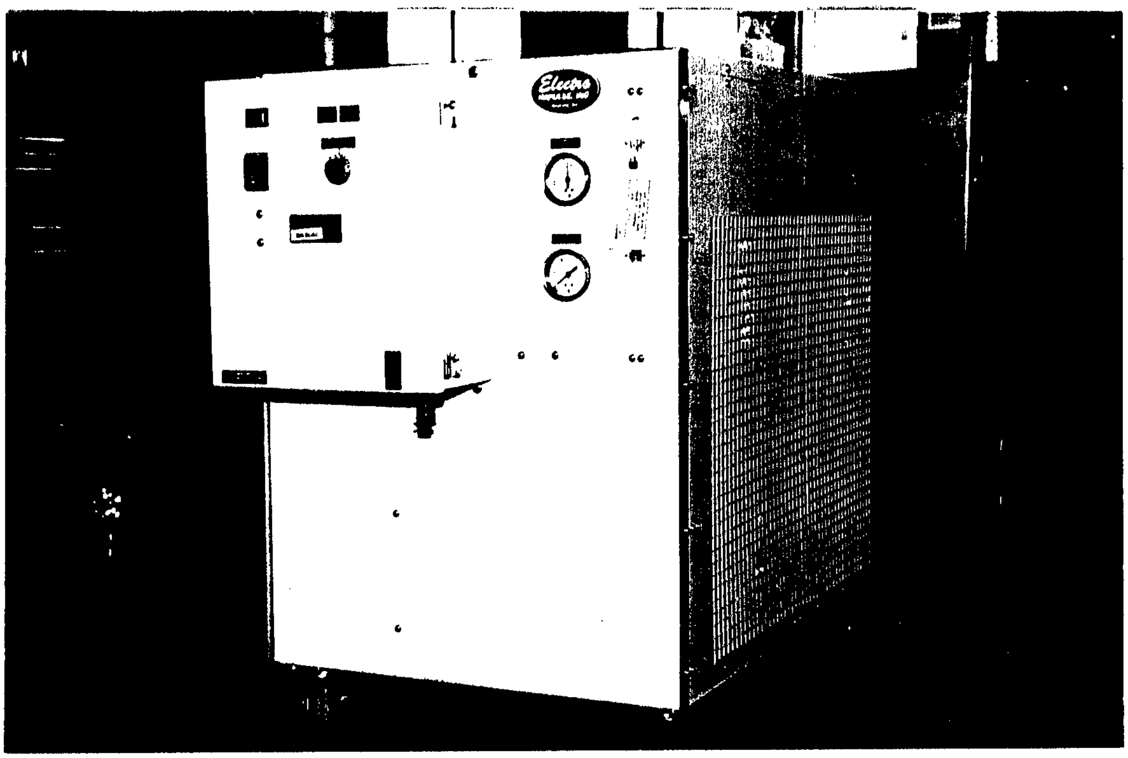


Figure 21. A picture of the refrigerated cooling unit.

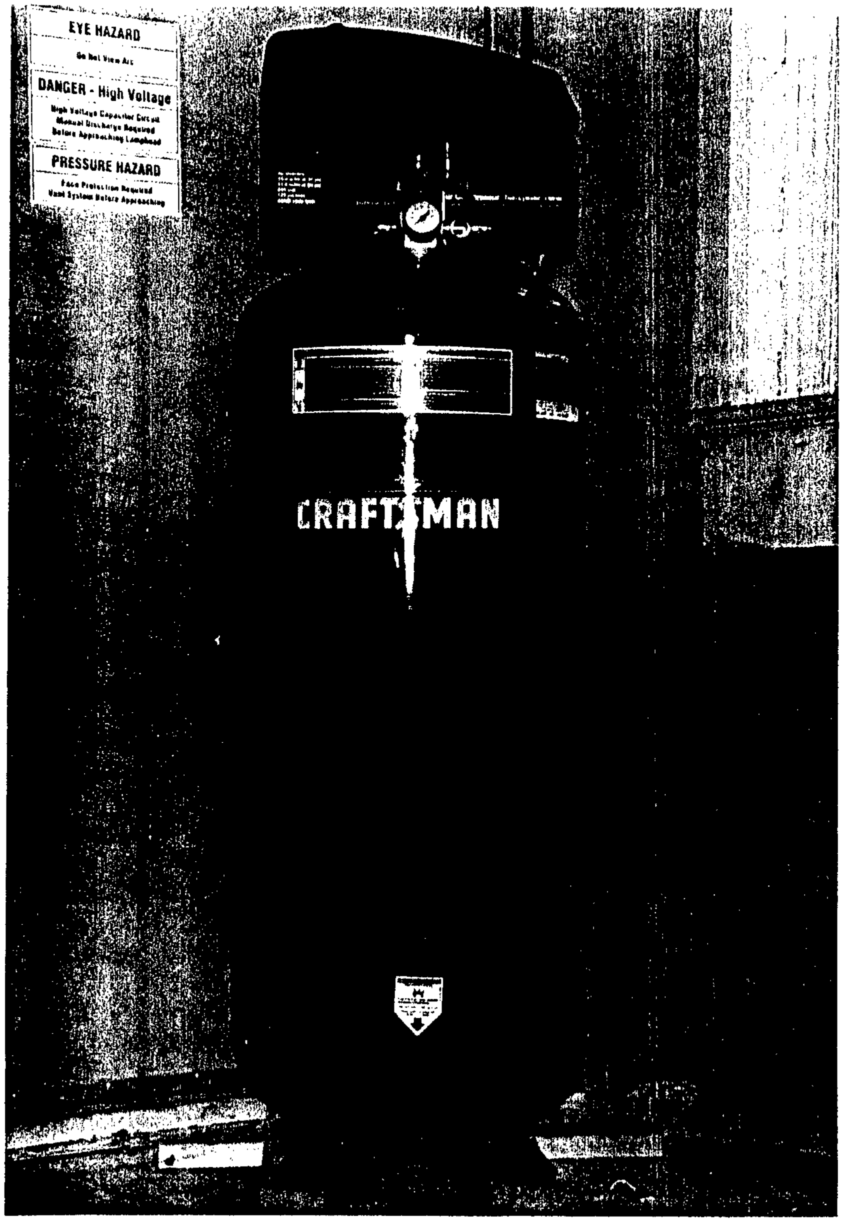


Figure 22. A picture of the air compressor.

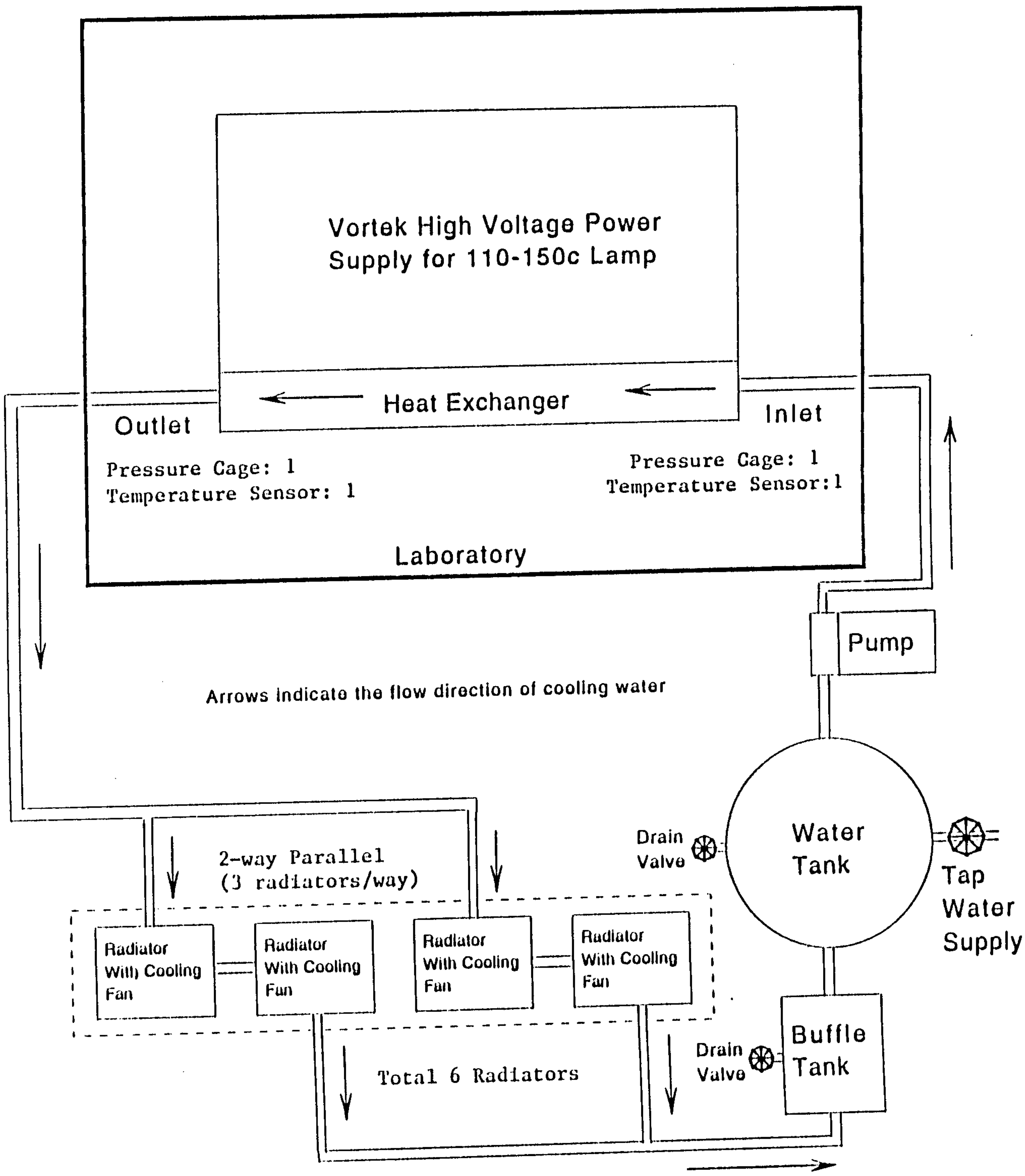


Figure 23. Schematic diagram of the outdoor cooling system for Vortek power supply and lamp system.

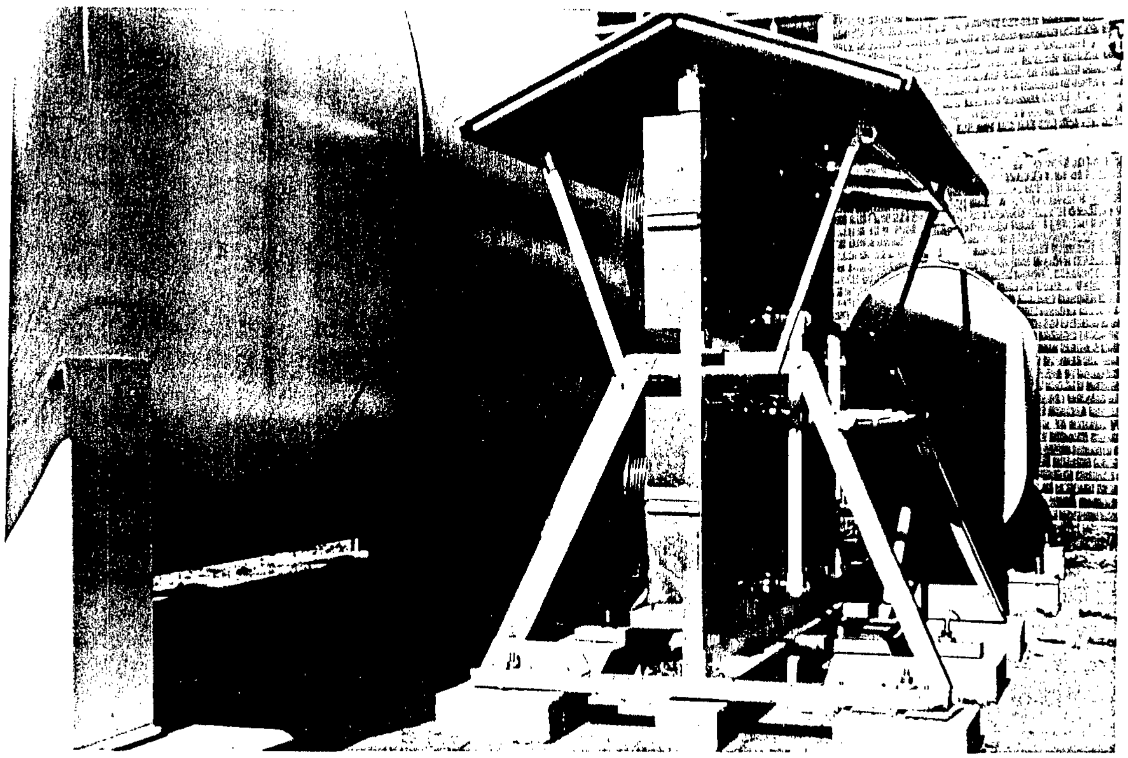


Figure 24. A picture of the outdoor cooling system with a portion of the vacuum tank.